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A LABORATORY INVESTIGATION OF THE EFFICIENCY OF DIFFERENT METHODS OF SOIL COMPACTION

A THESIS

Presented to

the Faculty of the Graduate Division

by

Clyde Marion Kennedy, III

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Civil Engineering

Georgia Institute of Technology

June 1953

A LABORATORY INVESTIGATION OF THE EFFICIENCY

OF DIFFERENT METHODS

OF SOIL COMPACTION

Approved:

Date Approved by Chairman: June 6, 1953

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ABSTRACT

Findings in compaction research in the Soils Laboratory of Georgia Institute of Technology led to the suspicion that at equal water content and equal total work different compaction methods did not produce identical density and strength characteristics in compacted soils.

For this reason an investigation was undertaken with a twofold purpose. The first was to ascertain which of several different methods of compaction produced greatest efficiency by comparison of the densities and strengths of soil samples compacted using these methods. The second was to determine the factors influencing compaction efficiency and the reasons for their influence.

For each method a series of compactions were performed at varied water contents by an amount of work which was held constant for all compactions. A special device called a punching-static compactor was devised for use as one method of compaction. This device was designed to simulate the action of a tamping roller more closely than do ordinary laboratory compaction methods. Other methods tested were dynamic and static compaction. The same soil, a silty clay, was used for all compactions. Compacted samples were tested for strength in triaxial compression. The data collected in density and strength tests was used to compare densities and strengths produced by the various methods at like quantity of work and equal water content.

These investigations led to the following conclusions. Compaction by different methods at like amounts of work and equal water

content does not necessarily produce equal amounts of compaction as expressed by dry density. Compaction by different methods at like amounts of work and equal water content does not necessarily produce equal strength characteristics in the compacted soil. Where total compactive energy, water content, layer thickness, and width of loaded area are held constant, the density and strength of a compacted soil are functions of the amount of energy applied per effort. Strength and density increase with increase in energy per blow or energy per effort. Methods which apply a greater portion of the total compactive energy per effort are the most efficient. Compaction which applies the total quantity of energy in one effort would be the most efficient compactive method for the soil tested.

INTRODUCTION

The problems undertaken in this thesis are those of (I) ascertaining which of several different methods of soil compaction give greatest efficiency by comparison of the densities and strengths of soil samples compacted using these methods and (II) determining the factors which influence this efficiency and the reasons for their influence.

With the advent of the automobile near the turn of the century, attention was drawn to the road system of the United States. The development of heavier vehicles with higher speeds made it abundantly clear that highways could no longer follow the natural topography, but that their curves and straightaways often would have to be routed through manmade cuts or over artificially placed fills. Studies of adequate subgrade conditions were undertaken. Many of the tests devised for subgrade analysis were borrowed from the agriculturist, and dissatisfaction with these procedures is apparent in the literature of the period.(1)

Particularly vexing were problems related to the control of artificially deposited materials. Manmade fill was used not only in road work but also in the construction of earth dams, and fills loosely deposited by dumping did not prove satisfactory. Their strength was low, their permeability high, and their settlement excessive. Experience showed, however, that materials which had been densified or compacted after placement proved stronger, less compressible, and less permeable than loosely deposited materials. The need for a knowledge of the compaction process and the factors affecting it became apparent.

In 1933 the results of extensive compaction research by the Bureau of Waterworks and Supply of Los Angeles were published in the Engineering News-Record by R. R. Proctor.(2) Mr. Proctor advanced not only a theory to explain the behavior of compacted soils but also a laboratory control method to determine the amount of compaction desirable and attainable. Since that time extensive compaction research has been performed to determine, among other things, the principles of soil action during compaction, new and better methods of compaction, and laboratory test procedures to approximate more closely field compaction. The present status of our knowledge of compaction is summarized in the next few paragraphs.

Soil compaction is a process in which soil particles are packed together more closely by forcing smaller particles to move into the spaces between larger ones. This packing increases the density of the soil and decreases its voids.

Compaction is measured quantitatively in terms of the dry density which is the weight of the soil solids per cubic foot of moist soil. The increase in dry density of a soil caused by compaction depends primarily on two factors, (I) the moisture content of the soil and (II) the amount of compactive energy applied.

For each soil there exists a definite relation of soil moisture content to the amount of compaction attainable for a given compaction procedure. This relation is shown in Figure 1 on the following page.

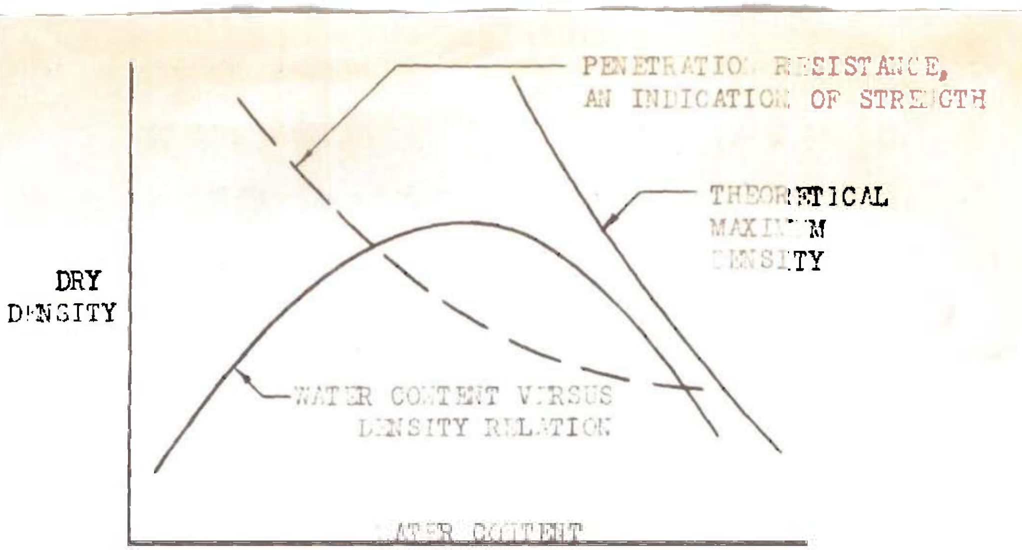


Fig. 1
MOISTURE-DENSITY CURVE

The compaction of a soil is opposed by a combination of the capillary tension of water films surrounding the soil particles and the viscosity of adsorbed layers of water attached to the particles themselves. Dry soils have high resistance to compaction, but addition of water lessens the effect of surface tension and allows the soil particles to build up larger, less viscous, adsorbed layers. The net effect is to increase workability and to allow the attainment of greater densities with no increase in compactive effort. The limit of this beneficial effect is reached when water fills all but a small portion of the soil voids, and increased workability can only be accomplished by replacing some soil particles with water. At this time the dry density of the soil-water mixture begins to decrease.

Therefore, for a given soil compacted at a given effort, there exists an optimum moisture content which permits attainment of maximum density. Equal dry densities are found at two locations on the moisture-dry density curve, one at a water content less than the optimum and one at a water content greater than the optimum. The strength of a soil compacted at less than optimum moisture would decrease to that of the soil with identical dry density at a water content greater than optimum should the fill later become water soaked. The maximum dependable strength occurs at optimum moisture content.

For all types of soil and for all compaction methods the maximum density attainable increases and optimum moisture content decreases with increase in compactive effort. At very high quantities of compactive effort a limiting dry density is reached which cannot be exceeded.

Only a small part of the compaction research to date has been systematized and great dependence has been placed on empirical findings. Little attention has been paid to the compaction process itself. The assumption has been made from Proctor's original presentation that for a given moisture content and a given quantity of work on a specific soil, the density and other properties attained are almost independent of compaction method.(3)

However, in the graduate soil laboratory at Georgia Institute of Technology, students noticed that a certain amount of work performed by static compaction using a hydraulic jack produced greater densities at like water contents than did greater amounts of work performed by dynamic compaction with a falling weight. It appeared, therefore, that at like quantities of work the densities produced would differ. Indications were also that at like amounts of work different methods of dynamic compaction produced different densities of soil. For this reason it was decided to investigate the relative efficiencies of various compaction methods as expressed by the differences in density and strength which they produced at like quantities of expended energy and equal water contents. It was hoped that the investigation would produce a knowledge of the factors governing the effectiveness of soil compaction processes, thus allowing a more intelligent approach to the design of compaction equipment and compaction methods than empirical knowledge permits.

A review of the literature available concerning compaction was undertaken. All pertinent references contained in the Industrial Arts Index and Engineering Index from 1925 to date were investigated. Of these, several proved informative about general aspects of compaction, particularly from the historical standpoint. However only two references presented information of the type sought.

The first of these was Soil Mechanics for Road Engineers produced by the Department of Scientific and Industrial Research Road Research Laboratory of the British Government. On pages 166-8 the authors present a comparison of moisture content-dry density curves produced by different compaction methods. They conclude that different dynamic methods produce equal dry densities at equal water contents and equal total work if the work per blow is the same. It is well to note that no attempt was made to investigate the similarity of moisture-density relations produced for the same total quantity of work by methods differing in energy applied per blow.

The second reference which proved of value is a series of reports on soil compaction studies conducted by the Corps of Engineers, United States Army, from 1949 to 1950. The whole series of reports gives valuable general data concerning the comparison of field and laboratory compaction procedures. Of special interest is the fourth report of the series which describes the effectiveness of very heavy compaction devices in producing good compaction in few trips over the area to be compacted.

EQUIPMENT

The major items of equipment used in the completion of the experimental program outlined in this report are listed below. These include:

I. Compaction devices

A. Dynamic compaction devices. (See Figure 2)

1. Five and one-half pound hammer with a twelve inch free fall.

2. Ten pound hammer with an eighteen inch free fall.

3. Modification devices for the ten pound hammer to convert it to a twenty-five pound hammer and adjustments for a twelve, a seven and two-tenths, and a three inch free fall.

B. Static compaction device - A hydraulic jack of forty thousand pound capacity equipped to exert its compactive effort through a piston of four inch diameter.

C. Punching-static device - A device exerting its compactive effort through a circular piston of one square inch end area. The necessary force is supplied by a lever arm to which is attached a pencil which records the travel of the lever arm during compaction operations. (See Figure 3)

II. Compaction mold - This mold is a steel cylinder of four inch inside diameter and four and six-tenth inch height. It is equipped with a base and a collar which holds loose soil to be compacted.

III. Triaxial shear equipment (See Figure 4)

A. A loading machine

B. A chamber in which test specimens can be subjected to confining air pressures during testing operations.

One major item used in this study is the soil itself. The soil used throughout the tests outlined in this report was a hard, moderately compressible, orange, low plasticity, sandy, silty clay. It was obtained from a pit behind the School of Civil Engineering at Georgia Institute of Technology. The specific physical properties of the soil are listed below.

Specific Gravity of Solids	2.72
Liquid Limit	39.9
Plastic Limit	24.5
Plasticity Index	15.4
Grain Size Distribution	(See Appendix)
Revised Public Roads Classification	A-6
Airfield Classification System	CL (An inorganic clay of low plasticity)

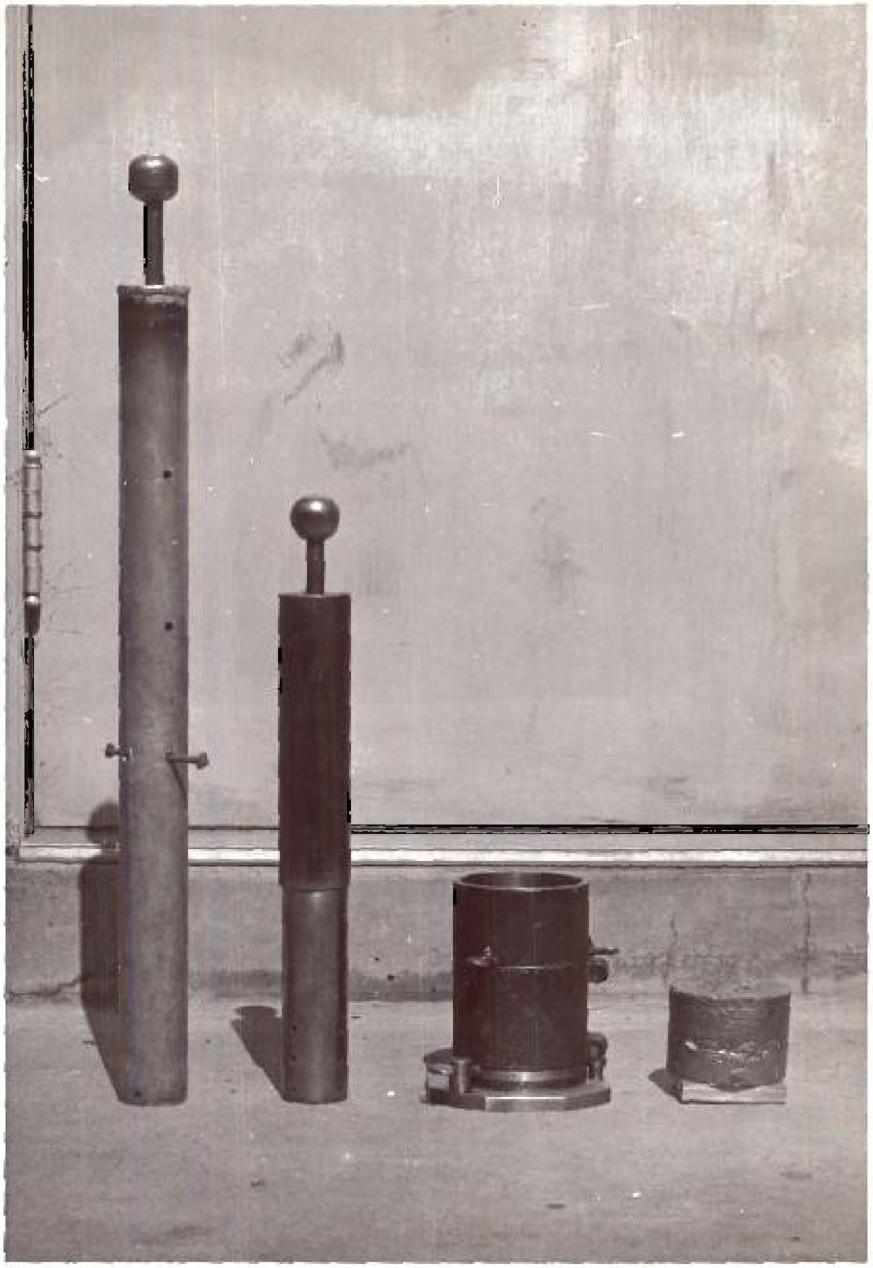


Fig. 2
DYNAMIC COMPACTION DEVICES
LEFT TO RIGHT, TEN POUND HAMMER, FIVE AND ONE-HALF POUND HAMMER, COMPACTION MOLD, AND TWENTY-FIVE POUND MODIFICATION FOR TEN POUND HAMMER

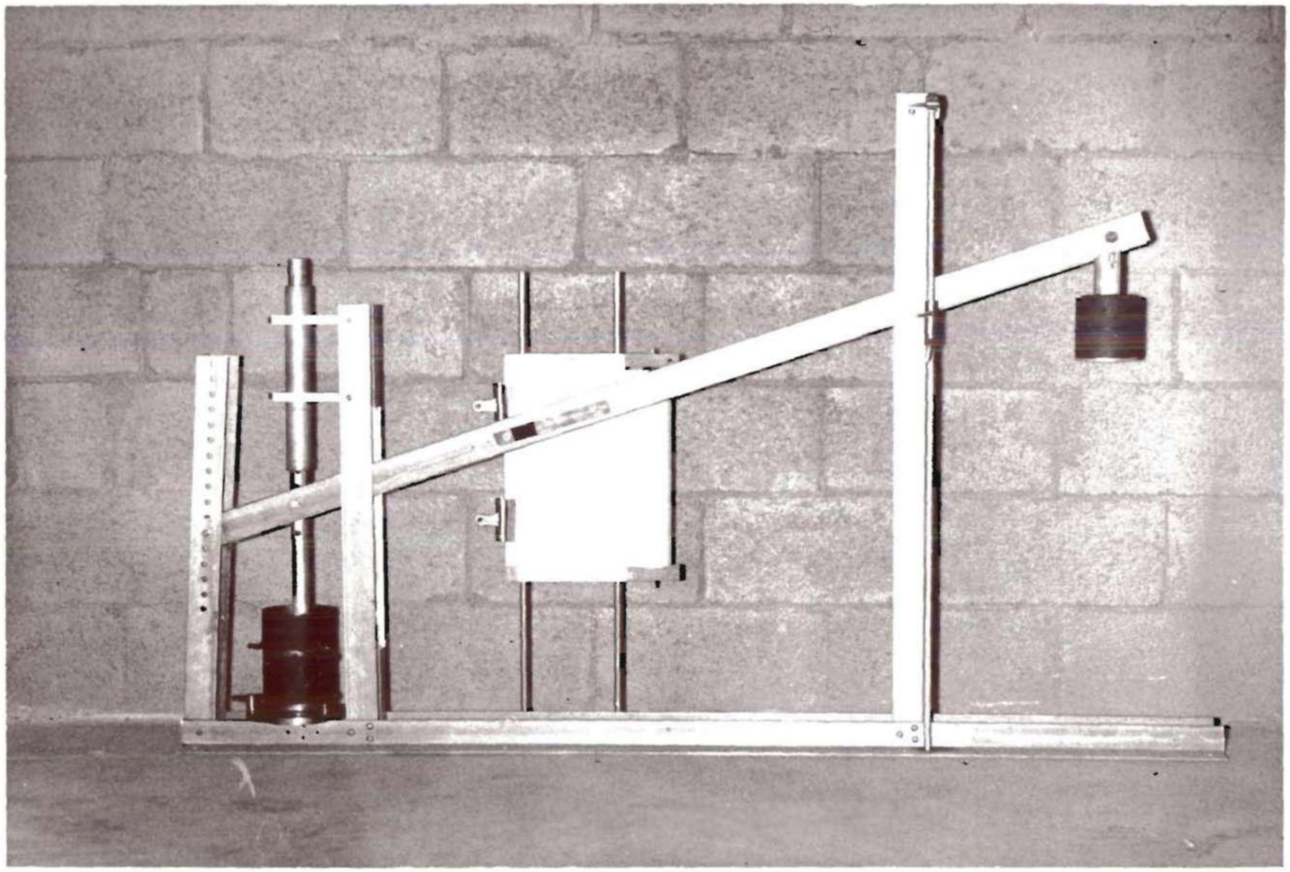


Fig. 3
PUNCHING-STATIC COMPACTION DEVICE

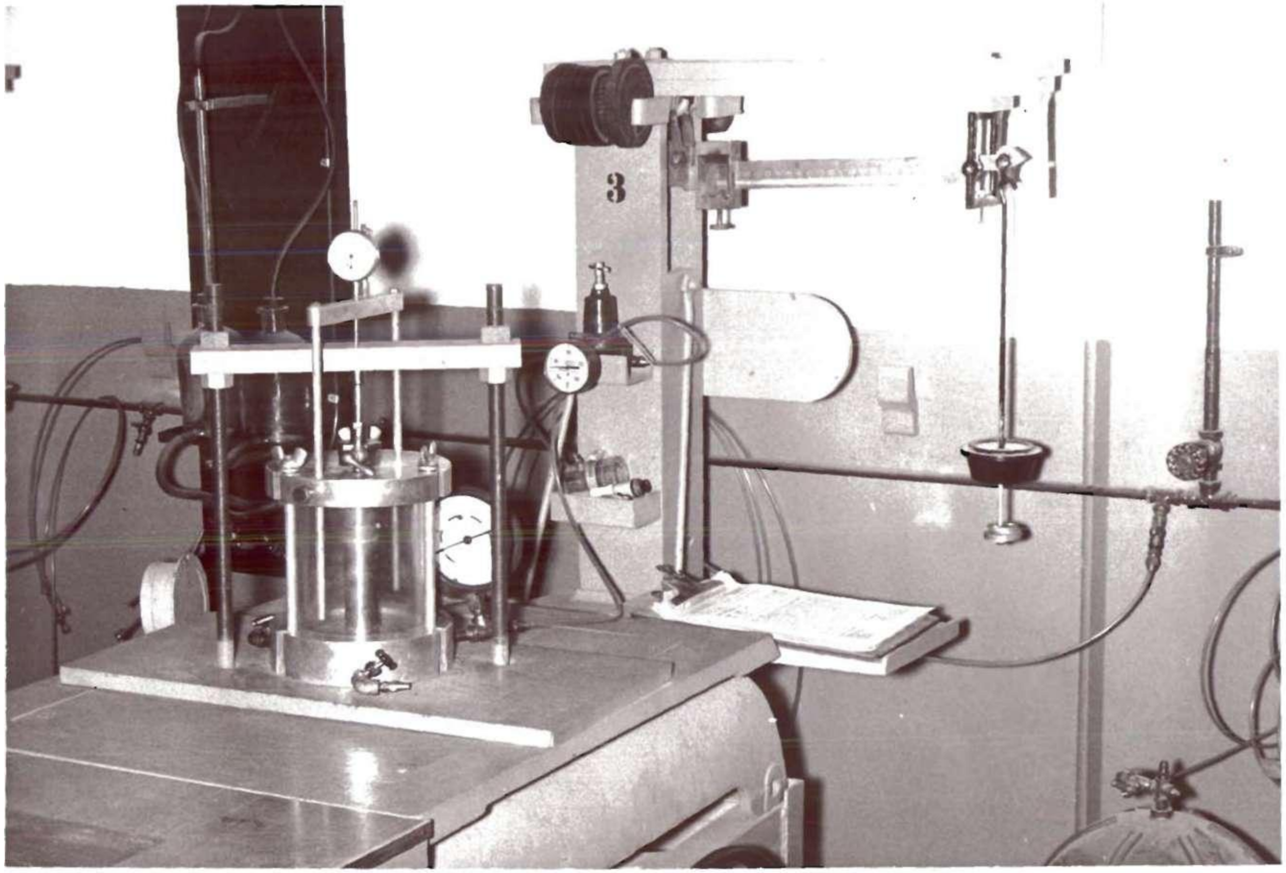


Fig. 4
TRIAXIAL SHEAR TESTING MACHINE

PROCEDURE

The test soil was brought indoors, placed in large flat pans, and allowed to air dry. The large lumps were broken up and the soil was screened through a sieve with square 0.185 inch openings. The material retained on the screen was discarded while that passing the screen was thoroughly mixed to insure uniformity and placed in covered containers.

Standard classification tests were performed on the soil. These included a specific gravity test to determine the specific gravity of soil solids,(4) a grain size analysis to determine the grain size distribution of the soil,(5) and the determinations of liquid and plastic limits to indicate the effect of water content on the soil.(6)

The water content of the test soil in the closed containers was determined daily. Soil samples of desired moisture content were prepared by adding the proper amounts of water to portions of soil removed from the storage containers, mixing the water in thoroughly, and enclosing the moist soil thus prepared in water tight containers overnight to allow the water to become completely distributed and adsorbed by the soil.

Though the various methods of compaction applied different amounts of compactive energy per effort, the total amount of work done was held constant for all compactions. This fixed quantity of total work was 33,750 foot-pounds per cubic foot and is the same as the energy expended in the three layer, modified Proctor compaction test. This quantity of work corresponds to field compaction with heavy equipment.

The procedure in obtaining compaction by dynamic methods will be described first. The dynamic procedures all consisted of compacting soil in the mold by means of a free falling weight striking the soil surface. The procedure typical to compaction by one of these dynamic methods will be described.

Six five-pound samples of the test soil were weighed out and the proper amounts of water were added to raise their water contents to ten, thirteen, sixteen, eighteen, twenty-one and twenty-four per cents respectively. The water was thoroughly mixed in and the samples were stored over night in water-tight containers as previously mentioned.

In compaction operations the can containing the soil was opened and the mold was half filled. The soil surface was leveled with light hand pressure. Compaction of the layer was now performed by the proper number of hammer blows evenly distributed over the soil surface. The compacted surface was then scarified to insure bonding of subsequent layers. Second and third layers of soil were compacted into the mold in like manner. Care was taken that the mold was completely filled. The soil surface was then planed off even with the top of the mold. The weight of the soil in the mold was now determined. This soil weight divided by the mold volume (one-thirtieth of a cubic foot) gave the wet density of the soil.

Now the compacted sample was carefully removed from the mold and a small representative portion cut from it for moisture content determination. The balance of the sample was coated with paraffin, labeled, and put away for later use. Knowing the water content and the wet density, the dry density of the sample could be computed. The work done on each dynamically compacted sample is the product of blows per layer, height of fall, weight of hammer, and number of layers.

In the static compaction each sample was prepared by means of the pressure of a piston forced against the soil by a hydraulic jack. The pressure was applied once to each layer. During the process the maximum compaction load was applied in increments and for each increment the travel of the piston recorded. A curve of pressure versus displacement was plotted for each of the three layers of a single compaction and the areas under these curves, which represent work, were integrated to give the total work done on a sample.

Because the quantity of work performed could not be controlled by regulating the number of hammer blows as in dynamic compaction, three compactions at each water content were performed at different maximum pressures and interpolation based on the proper amount of work (33750 foot-pounds per cubic foot) was used to determine the density.

The use of three compactions at like water content entailed the mixing of six fifteen-pound soil samples, one at each of the following percentages by weight of water; ten, thirteen, sixteen, eighteen, twenty-one, and twenty-four. However because of the distortion of the loading machine frame at hydraulic jack loads in excess of 20,000 pounds, it was impossible to perform compactions of the soil samples at twenty-one and twenty-four per cent moisture.

The details of mold filling, scarifying, weighing, water content determination, paraffin coating, and dry density computation were the same as those for the dynamic compactions previously described.

In compactions performed by the punching-static method the compacting energy was furnished by means of a piston of one square inch end area which started from rest at the soil surface, then, actuated by a falling weight attached to the loading lever, performed the compactive work. In order that the piston would not travel entirely through the thin soil layers in the mold furnishing little compaction, a precompaction pressure of 19.9 pounds per square inch was applied to the soil surface by means of a four inch diameter piston affixed to the end of the small loading piston. After precompaction, the main compactive work was performed by a certain number of strokes of the small loading piston distributed evenly over the soil surface. The travel of the loading piston during both precompaction and compaction operations was recorded by a pencil attached to the loading lever arm. The total work performed in each compaction was computed as the product of the number of layers (three) the total travel of the loading piston and the force applied by the loading piston.

Because the travel of the loading piston could not be exactly controlled, three samples at the same water content had to be prepared for punching static tests just as for static compactions. Interpolation for density attained at a compactive effort of 33750 foot-pounds per cubic foot was also performed as for the static compaction. Other details of compaction procedure were identical with those mentioned for the two previous types of compaction.

Also desired for purposes of this investigation was a knowledge of the compacted soil properties as determined by testing of samples in triaxial shear. The triaxial testing of one compaction sample will be described in the following paragraphs.

The paraffin coating was removed and from the sample were carved three cylindrical triaxial test specimens approximately three and one half centimeters in diameter and seven centimeters long. The triaxial specimens were fitted with caps through which load could be applied by the loading machine and encased in air tight rubber membranes. They were subjected to confining pressures of zero pounds per square foot for one specimen, fifteen hundred pounds per square foot for the second specimen, and four thousand pounds per square foot for the third specimen. Then they were loaded to destruction. Failure was assumed to have occurred when test specimens either sheared suddenly or underwent a strain of fifteen per cent.

From failure loads and average area of test specimen the failure stress of each specimen was computed. By the use of the failure stresses of the three specimens from each soil sample, Mohr's circles were constructed and the apparent cohesion and angle of internal friction of each soil sample were determined.(7) In this discussion, apparent cohesion will be understood to mean the intercept of the Mohr envelope with the vertical axis. Also the angle of internal Friction is the angle between the Mohr envelope and the horizontal. Determination of both of these quantities is based on the assumption of a straight line Mohr envelope.

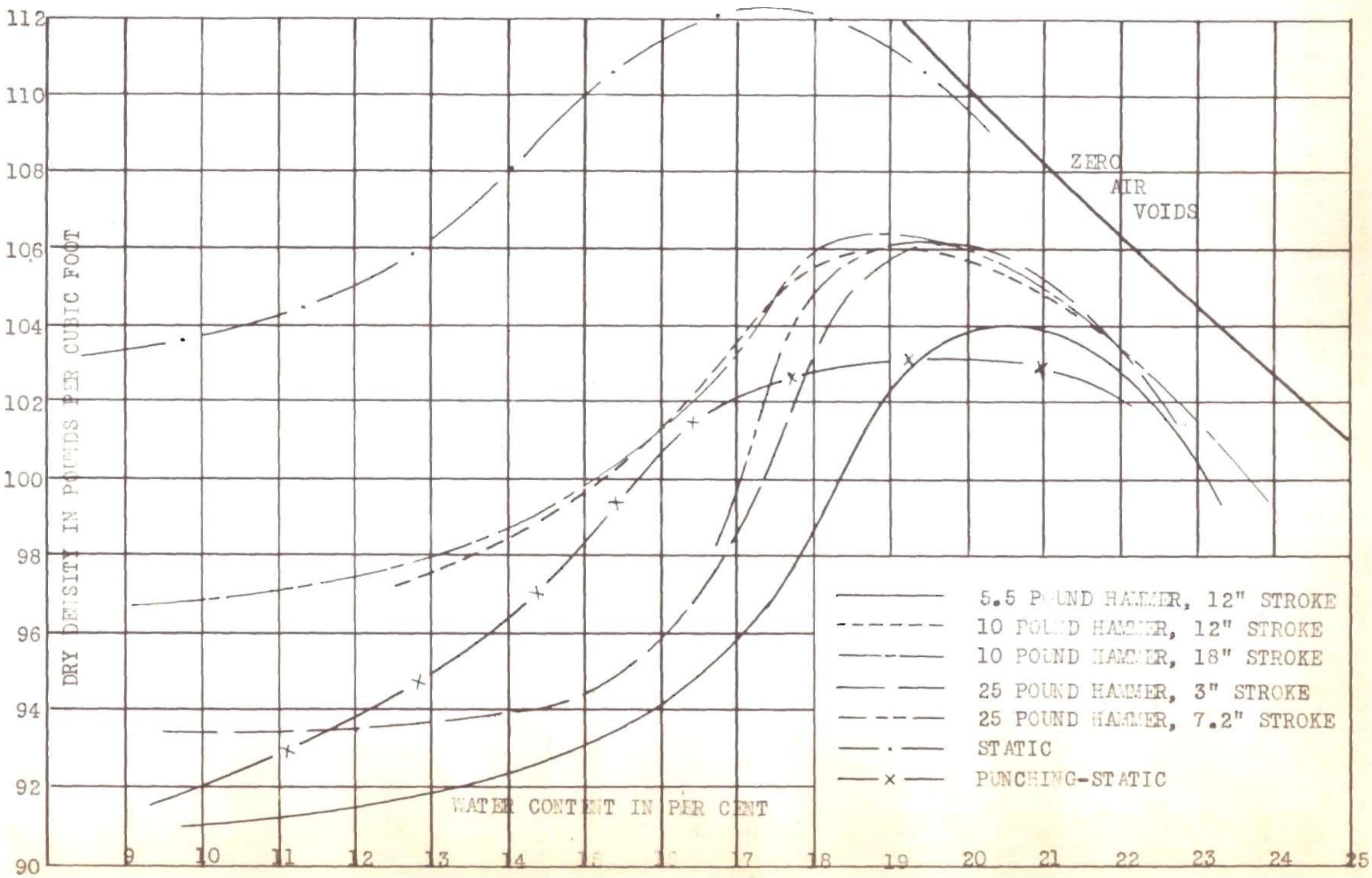


Fig. 5
MOISTURE-DENSITY CURVES FOR ALL COMPACTIONS PERFORMED

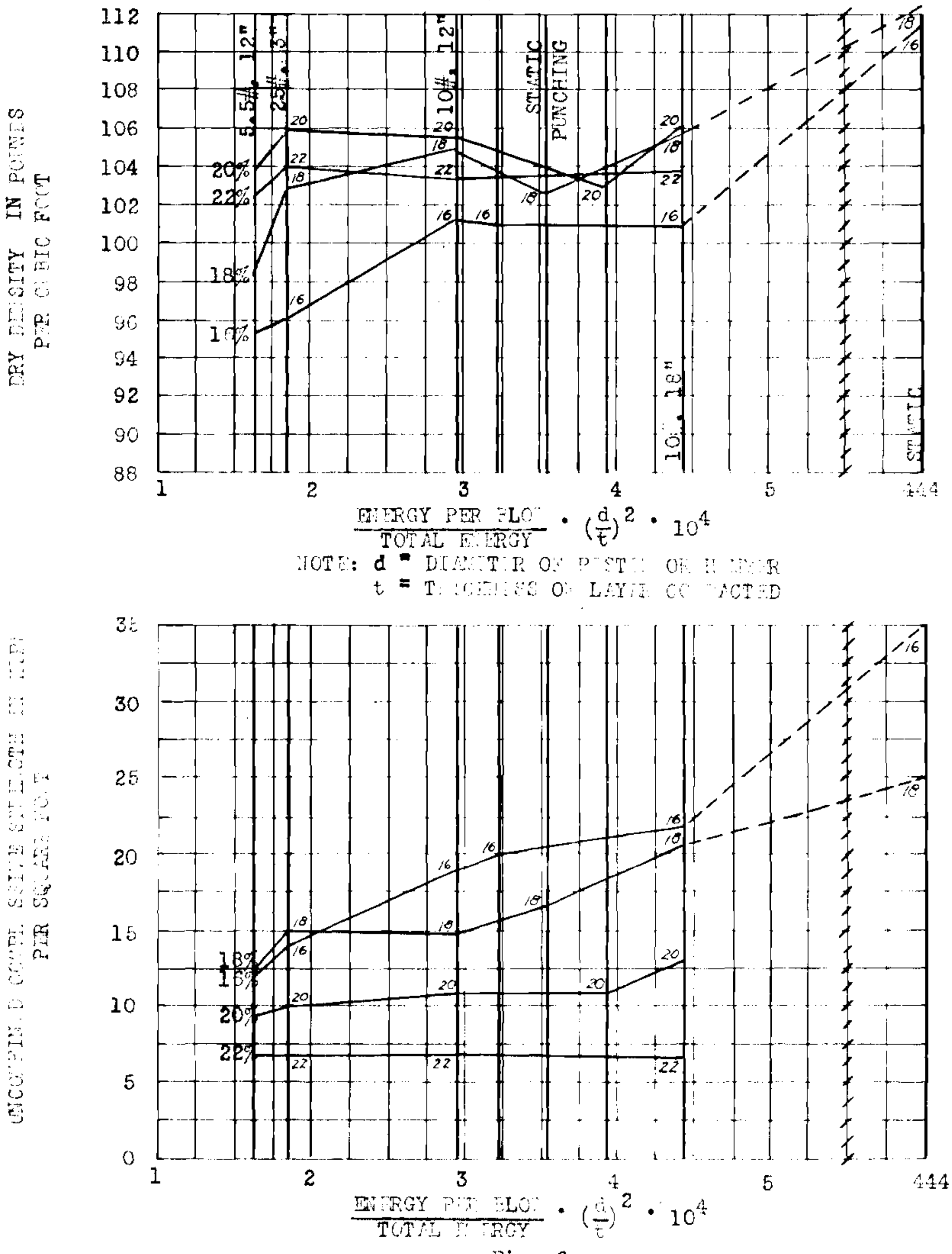


Fig. 6

MODIFIED ENERGY PER BLOW RELATIONSHIPS AT VARIOUS WATER CONTENTS

DISCUSSION OF RESULTS

Analysis of the data collected from the compaction and triaxial shear testing of samples began with the plotting of conventional moisture-dry density relations for the various compaction methods. These individual relations showed little difference from ordinary relations of the moisture-dry density type. On these plots were superimposed contours of apparent cohesion, unconfined compressive strength, and angle of internal friction. Both relations and superimposed contours are shown in detail in the appendix. The conclusions reached in this report have come from comparisons of the relations and contours resulting from various compaction methods.

Inspection of Figure 5 provides several general observations. First it will be noticed that compaction by different methods at like amounts of work and equal water content below optimum do not necessarily produce equal amounts of compaction expressed in dry density. Static compaction provides greater compaction at equal amounts of work than does either the dynamic or the punching-static method previously described. Further, compaction by the ten pound hammer falling eighteen inches gives better results than any other dynamic compaction device tested. At water contents in excess of the optimum, densities produced by various methods do not differ appreciably.

From the comparison of moisture-dry density curves for like quantities of work by different methods it is obvious that the densities produced at like water contents are not identical. The factors influencing compaction should therefore be investigated to discover an explanation for the difference. Furthermore, comparisons of apparent cohesion, angle of internal friction, and unconfined compressive strength possessed by samples compacted by different methods also show marked differences.

The primary variable influencing compaction characteristics is the soil used. Each soil acquires different strength and density properties from compaction. To eliminate this largest variable, the same type of soil was used throughout all of the tests reported in this investigation. Other variables which affect the soil itself and which must be considered are water content, total quantity of work, amount of work per application, weight of compacting parts, velocity of impact, diameter of loaded area, depth of soil being compacted, and confining effects of the compaction mold.

In any investigation of the quantities influencing compaction, water content is certainly an important consideration. Studies by Proctor and subsequent investigators have shown the definite relation between water content and density. However, since samples prepared in this investigation were mixed and stored identically and were compared at like water contents, the variable of water content was definitely controlled during research operations.

As mentioned earlier in this thesis, total quantity of work certainly affects the degree of compaction of a soil, for density and strength increase with total compactive effort. In this study, the effects of differing quantities of compactive effort were eliminated by comparing all compactions at equal amount of total work.

A third influencing agent worthy of attention is the amount of work per application. For dynamic compaction this quantity can readily be expressed as work in foot-pounds per blow. Because of the fiscous nature of the water layers adsorbed on soil particles, the amount of compactive energy per effort might well affect the amount of energy lost as heat. Further, when one considers soil particles to be held together by the surface tension of intergranular water, it is reasonable to assume that differences in efficiency of compaction would occur depending on whether the process of compaction were accomplished by a few large distortions of structure or many small ones.

Hammer weight is a quantity which might be called a contributing factor in that its effect is noticed in expressions of momentum and amount of work per application. The mere presence of five and one-half, ten, or twenty-five pound weights on the soil surface may produce very little compaction. One effect of weight worth considering, however, is pressure. The concentration of load per unit area definitely affects compaction. This can readily be observed from the high densities of statically compacted samples.

The effect of velocity of impact may be considered in two ways. It first combines with hammer mass to determine the momentum delivered by the dynamic methods. The momentum transfer involved in these methods might well introduce losses which would lower their efficiencies. The zero velocity of impact of static and punching static methods gives them momentum values of zero. Secondly, the impact velocity of the dynamic methods once again combines with hammer mass to determine the kinetic energy delivered to the soil to be compacted and definitely affects the amount of energy per blow they are capable of delivering.

Diameter of piston or of loaded area is a factor whose effect on degree of compaction and strength characteristics of a soil must not be overlooked. In cohesionless soils, which are more or less represented by soils at moisture contents less than optimum, the bearing capacity varies as the width of the loaded area.(8) This means that soils confined under areas could withstand higher compacting pressures without shearing and consequent loss of efficiency than could soils compacted under narrow ones. Diameter also has importance because it influences the pressure at any point in the soil mass, which according to Boussinsesq, is proportional to diameter of the loaded area divided by the square of the depth to the point.

Depth of the compacted soil layer must also be considered in compaction investigations. The nearness of the rigid mold bottom or of previously compacted layers affects both the magnitude and the distribution of the compactive pressure caused by effort applied at the surface. Layer thickness further enters compaction considerations, for it limits to the bottom of the compacted layer the Z depth expressed by the Boussinesq expression diameter $/Z^2$. To eliminate any possible effects of depth differences the depths of all soil layers in this investigation were made equal.

All previous factors mentioned might well have been encountered under field conditions. A final factor peculiar to laboratory procedure must be mentioned. This is the confining effect of the mold. This effect produces two opposing results. The first of these is that it hampers natural displacement of soil under loads and permits the creation of stresses in the soil which otherwise could not be attained. Secondly, soil tends to arch across the mold furnishing strength which opposes compaction. These effects of confinement would not be so pronounced in dynamic and punching-static methods in which the compacting piston was but a fraction of the mold area as in the static method in which mold and piston areas were equal. This observation indicates that efficiencies attained in static compaction may differ from those attained by field compaction.

In determining which of the aforementioned variable factors may have produced the observed differences in compaction and strength, it was desirable to consider as many as possible of these variables simultaneously. It should be noted here that though strength and density varied in much the same manner throughout the tests, enough difference in their values is apparent from a study of the relations presented to preclude the idea that strength is a sole function of density. Rather they must be considered as two coincident effects resulting from compaction. H. C. Porter in the Engineering News-Record has said, "Density of a consolidated clay soil as usually measured in pounds per cubic foot is not always a criterion of its compressive strength."(9)

The first relations devised were dry density versus impact velocity and strength versus impact velocity with comparisons of the various methods at equal water contents. (See Appendix). In these comparisons, however, no allowance is made for weight effects, and as would be expected no definite relation between dry density and impact velocity or between strength and impact velocity could be discovered.

Momentum takes into account both impact velocity and weight (more properly, mass) of the compacting hammer. Therefore momentum-density and momentum-strength relationships at like water contents were sought. A computation of momentum for static and punching-static compactions gives a value of zero and leads to the rather unjustified conclusion that a very small mass applied to the soil at zero velocity would produce the same compaction as a very large mass applied to the surface. Though momentum-density and momentum-strength relationships obviously do not exist for static and punching-static compaction methods it was still hoped that such a relationship might be found for the various dynamic compaction methods. This relationship likewise proved nonexistent. (See Appendix)

Next, a relationship between energy per blow (energy per effort) and density, or energy per blow and strength was sought. All compaction methods could be considered in this study, for in each method some effort existed which could be considered as one blow. Comparison of both strength versus energy per blow and density versus energy per blow at like water contents showed a definite trend toward increasing densities and strengths with increased energy per application. These trends as indicated by energy per blow-strength relationships were much more pronounced and definite than the trend indicated in energy per blow-density relationships. However the densities and strengths produced by the punching-static method did not seem to fit this trend. One important difference between the dynamic method employed and the punching-static method was the difference in size of compaction pistons. (The punching-static piston was 1.128 inches in diameter as compared to the two inch diameter dynamic hammer face.) This consideration had not entered previous relations which either did not apply to static and punching-static compaction or were invalidated by lack of any correlation even among the dynamic compaction methods in which the hammer diameter remained constant.

As previously asserted, piston diameter has two effects on compaction. First it influences the intensity of load a soil can withstand without shearing and dissipating energy of compaction. Second, it affects the intensity of effective compactive stress which accomplishes the work of moving particles. The double effect of diameter suggests the dimensionless ratio $d \cdot d/Z^2$ in which d represents diameter and Z the depth of a point in the soil. In this ratio the first term denotes the increased bearing effect, the second the pressure effect. Since the only fixed point during compaction is the bottom of the soil layer being compacted, Z in the above ratio is replaced by t, the thickness of the soil layer. The ratio is the expressed as $(\frac{d}{t})^2$.

New relations of density and strength versus energy per blow as modified by the $(\frac{d}{t})^2$ ratio were now sought. In order to render the relations as nearly dimensionless as possible, energy per blow expressed in foot pounds was divided by the constant total amount of work in foot pounds.

The new relations showed ordinates of strength and density versus abscissas of $\frac{\text{energy per blow}}{\text{total energy}} \cdot (\frac{d}{t})^2$. The strength and density ordinates at moisture contents of sixteen, eighteen, and twenty per cent showed a definite trend of increase with increase of the abscissa. (See Figure 6) Further, several arbitrary points of known water content and density were selected, and at these points densities and strengths produced by various means of compaction were plotted versus $\frac{\text{energy per blow}}{\text{total energy}}$ • $(\frac{d}{t})^2$. Once again the ordinates of strength increased with energy per blow as modified by the $(\frac{d}{t})^2$ ratio.

The interpretation of these results leads to the following conclusion: For equal compactive effort, water content, layer thickness, and piston diameter, greater density and strength of a compacted soil is produced by greater amounts of compactive energy per application. Or, to restate the above, for equal compactive effort, water content, layer thickness, and piston diameter, greater efficiency of compaction is attained with greater amounts of compactive energy per effort. This leads to the conclusion that one can do a better job of compaction with the same amount of work if he can apply it in large amounts instead of small ones. The good results which the Corps of Engineers has attained in compaction tests with few passes of heavy rollers seem to confirm this idea.(10) The limit of the beneficial effects of application of compactive energy in large amounts would, of course, be reached when equipment weight caused bearing failure of the soil to be compacted. The d/t ratio seems to have an important effect on compaction, and results indicate that, all other things being constant, better compaction occurs with increasing values of this ratio.

At water contents in excess of optimum, increase in amount of energy per blow has little effect on density and strength. On this branch of the moisture-dry density curve the theoretical maximum is being approached, and increase in energy per effort can accomplish little additional compaction.

At the same time that the first energy per blow versus strength and density relations were being investigated, it was noted that the value of energy expended by one blow expressed in foot pounds per cubic foot reduced to a quantity with the dimensions of a pressure (pounds per square foot). This value was called a "dynamic pressure" and a dimensionless ratio was set up between it and static pressure as expressed by hammer weight divided by area. This relation between work per blow and static pressure would seem to account for both the amount of work per application and intensity of the stress which produced the work. However, density and strength plotted versus the ratio showed no definite trends even among dynamic compaction devices. Therefore this comparison was abandoned without any attempt to adjust it by the $(\frac{d}{t})^2$ ratio.

CONCLUSIONS

The following conclusions have been drawn from this research:

1. Compaction by different methods at like amounts of work and equal water content does not necessarily produce equal amounts of compaction as expressed by dry density.
2. Compaction by different methods at like amounts of work and equal water content does not necessarily produce equal strength characteristics in the compacted soil.
3. Where total compactive energy, water content, layer thickness, and width of loaded area are held constant, the density and strength of a compacted soil are functions of the amount of the energy applied per effort. Strength and density increase with increase in energy per blow or energy per effort.
4. Methods which apply a greater portion of the total compaction energy per effort are the most efficient. Compaction which applies the total quantity of energy in one effort would be the most efficient compaction method for the soil tested.

RECOMMENDATIONS

Compaction, in addition to affecting strength and density characteristics of a soil, influences the permeability, swell-shrink, and consolidation properties. Time limitations precluded the possibility of conducting these other investigations concurrent with the preparation of the studies presented in this thesis. However, portions of all samples tested were carefully preserved and labeled so that further studies may be made concerning the effect of increasing energy per effort on the consolidation, swell-shrink, and permeability properties of a clay soil. Such studies are recommended to round out the program of investigation already undertaken.

Indications are that the beneficial effects of increasing energy per effort may increase at a decreasing rate as higher and higher portions of the total work are applied at one time. This trend should certainly be investigated to discover, if possible, whether some point is reached past which little better results expressed in density and strength can be obtained.

The ratio of the diameter of the compacting foot or hammer to the thickness of the soil layer is a factor in soil compaction well worth investigating. Definite findings concerning this ratio could radically affect the design of compaction equipment.

The punching-static compaction device, especially designed for these tests, shows promise of closely approximating field compaction by tamping rollers. This device should be employed using larger piston area and higher loadings to check its suitability in simulating field conditions. If possible its results should be compared with those produced by construction machinery.

The intensities of dynamic pressures (stresses) created in soil by compaction methods seem to have definite effects on the compaction process. The derivation of an energy per blow-dynamic pressure relationship may be found in the Appendix. The validity of this relationship and the dynamic pressure effect on compaction are worthy of further experimental study.

A P P E N D I X

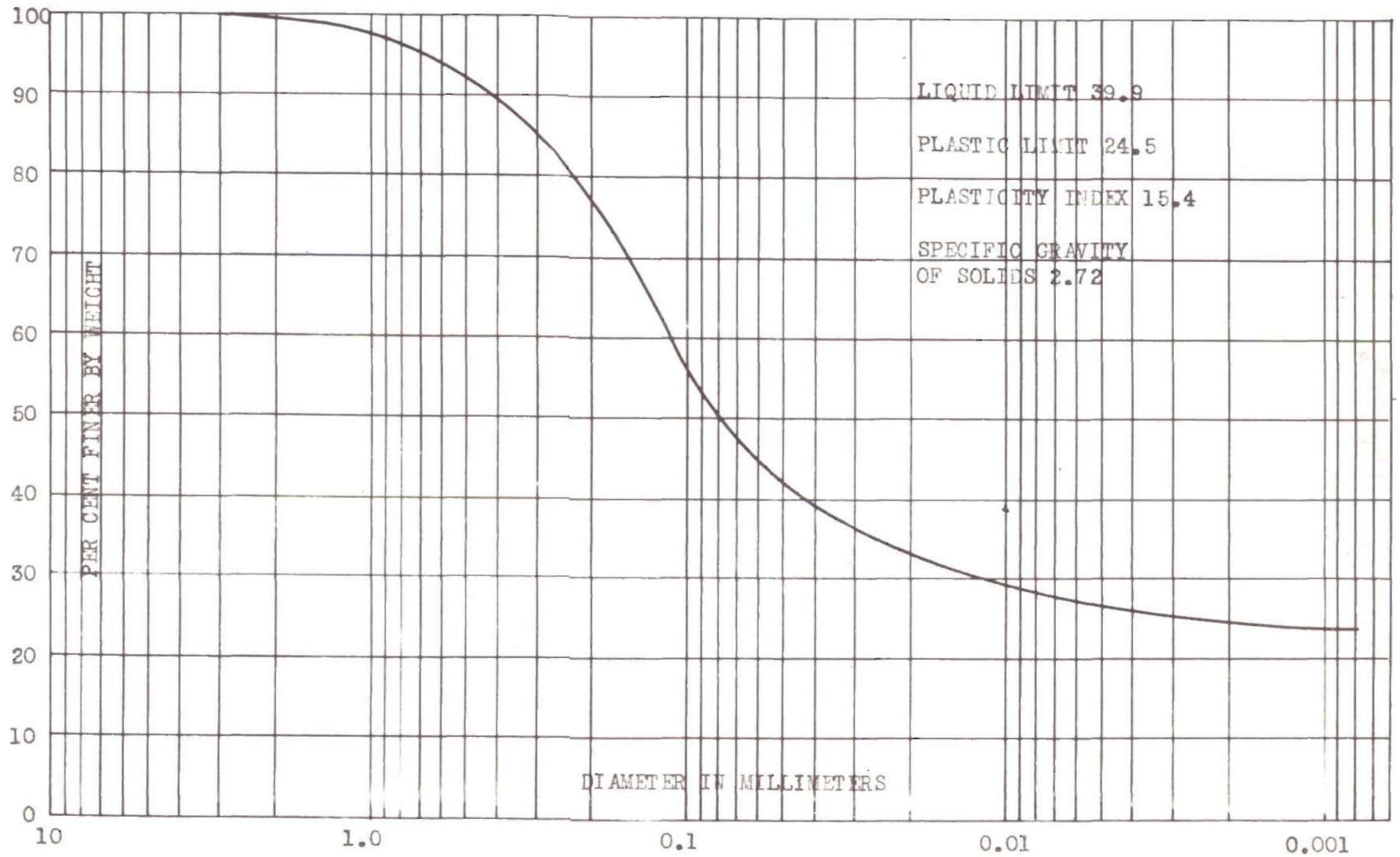


Fig. 7
GRAIN SIZE DISTRIBUTION OF TEST SOIL

TABLE 1

COMPACTION METHOD	SAMPLE DESIGNATION	WORK (33750 FT-LB/FT^3 UNLESS NOTED)	WATER CONTENT IN PER CENT	WEIGHT OF SOIL IN COMPACTION MOLD IN LB.	WET DENSITY IN LB/FT^3	DRY DENSITY IN LB/FT^3	CONFINING PRESSURE IN LB/FT^2	DEVIATOR STRESS IN LB/FT^2	APPARENT COHESION IN LB/FT^2	ANGLE OF INTERNAL FRICT. IN DEGREES	UNCONFINED COMPRESSIVE STRENGTH LB/FT^2
PUNCHING - STATIC COMPACTION ; 3 LAYERS	1-1	40700	9.54	3.38	98.9	90.4					
	1-2	32500	9.59	3.40	99.5	90.9					
	1-3	35800	9.23	3.45	101.0	92.4					
	2-1	30300	13.62	3.58	104.8	92.2	0	4560	1250	47°	4560
							1500	17880			
							4000	27800			
	2-2	37300	12.98	3.75	109.9	97.3	0	9970	2500	43.5°	9970
							1500	22550			
							4000	26950			
	2-3	30700	13.09	3.66	107.1	94.7	0	8560	1500	48.5°	8560
							1500	18220			
	3-1	31700	15.79	3.96	116.0	100.2	0	18880	5500	31°	18880
							1500	25500			
							4000	28000			
	3-2	31100	16.44	3.96	116.0	99.6	0	16020	4000	40.5°	16020
							1500	21950			
							4000	31100			
	3-3	40200	16.30	4.07	119.2	102.4	0	21850	6250	31°	21850
							1500	26550			
							4000	31000			
	4-1	36800	19.22	4.20	123.0	103.2	0	15000	5000	26°	15000
							1500	19500			
							4000	21700			
	4-2	35300	18.60	4.18	122.3	103.2	0	14600	4250	32°	14600
							1500	18850			
							4000	23700			

TABLE 2

COMPACTION METHOD	SAMPLE DESIGNATION	WORK (33750 FT-LB/FT^3 UNLESS NOTED)	WATER CONTENT IN PER CENT	WEIGHT OF SOIL IN COMPACTION MOLD IN LB	WET DENSITY IN LB/FT^3	DRY DENSITY IN LB/FT^3	CONFINING PRESSURE IN LB/FT^2	DEVIATOR STRESS IN LB/FT^2	APPARENT COHESION IN LB/FT^2	ANGLE OF INTERNAL FRICT. IN DEGREES	UNCONFINED COMPRESSIVE STRENGTH LB/FT^2
PUNCHING-STATIC 3 LAYERS	4-3	30200	17.64	4.11	120.2	102.3	0	15260	5000	27.5°	15260
							1500	20850			
							4000	22450			
	5-1	33500	21.20	4.25	124.4	102.6					
	5-2	27700	21.90	4.21	123.2	101.2	1500	10010	3000	19°	8170
	5-3	42100	19.98	4.34	127.0	106.0	0	8170			
25 LB HAMMER; 12" STROKE; 15 BLOWS PER LAYER; 3 LAYERS 25 FT-LB PER BLOW	SPEC6		18.79	4.30	125.9	106.1					
	SPEC7		22.25	4.30	125.9	103.1					

TABLE 3

COMPACTION METHOD	SAMPLE DESIGNATION	WORK (33750 FT-LB/FT^3 UNLESS NOTED)	WATER CONTENT IN PER CENT	WEIGHT OF SOIL IN COMPACTION MOLD IN LB.	WET DENSITY IN LB/FT^3	DRY DENSITY IN LB/FT^3	CONFINING PRESSURE IN LB/FT^2	DEVIATOR STRESS IN LB/FT^2	APPARENT COHESION IN LB/FT^2	ANGLE OF INTERNAL FRICT. IN DEGREES	UNCONFINED COMPRESSIVE STRENGTH LB/FT^3
STATIC COMPACTION; 3 LAYERS	S-1-1	45440	8.31	4.17	122.0	112.7					
	S-1-2	28040	8.99	3.82	111.9	102.6					
	S-1-3	28560	8.56	3.76	110.1	101.3	0	23500	6500	43°	23500
							1500	29650			
							4000	38650			
	S-2-1	33680	11.62	3.98	116.5	104.4	0	34850	7000	47.5°	34850
							1500	37800			
							4000	57900			
	S-2-2	38320	11.49	4.01	117.3	105.2					
	S-2-3	30600	11.87	3.95	115.7	103.3					
	S-3-1	38280	13.76	4.30	125.9	110.8					
	S-3-2	33200	14.92	4.28	125.1	109.0	0	40200	8700	42.5°	40200
							1500	38600			
							4000	57400			
	S-3-3	39760	14.57	4.36	127.7	111.2					
	S-4-1	25760	18.78	4.48	131.0	110.3					
	S-4-2	29960	19.16	4.51	132.0	110.7					
	S-4-3	38560	17.31	4.56	133.3	113.7	0	26600	5500	46.°	26600
							1500	40400			
							4000	37650			

TABLE 4

COMPACTION METHOD	SAMPLE DESIGNATION	WORK (33750 FT-LB/FT^3 UNLESS NOTED)	WATER CONTENT IN PER CENT	WEIGHT OF SOIL IN COMPACTION MOLD IN LB.	WET DENSITY IN LB/FT^3	DRY DENSITY IN LB/FT^3	CONFINING PRESSURE LB/FT^2	DEVIATOR STRESS LB/FT^2	APPARENT COHESION IN LB/FT^2	ANGLE OF INTERNAL FRICT. IN DEGREES	UNCONFINED COMPRESSIVE STRENGTH LB/FT^2
25 LB. HAMMER; 3" STROKE; 60 BLOWS PER LAYER; 3 LAYERS; 6.25 FT-LB PER LAYER	H-1		7.96	3.45	101	93.5					
	H-2		11.43	3.56	104.1	93.5	0	7210	1750	46°	7210
							1500	18680			
							4000	26700			
	H-3		15.74	3.73	109.1	94.4	0	13240	3000	42°	13240
							1500	19920			
							4000	29000			
	H-4		17.58	4.07	119.0	101.2	0	17540	4000	41°	17540
							1500	24550			
							4000	32000			
	H-5		20.05	4.35	127.2	106.1	0	10000	3250	27.5°	10000
							1500	14320			
							4000	17600			
	H-6		22.90	4.24	124.0	101.0	0	4340	1500	20°	4340
							1500	6640			
							4000	8040			
25 LB HAMMER; 7.2" STROKE; 25 BLOWS PER LAYER; 3 LAYERS; 15 FT-LB PER BLOW	Z-3		16.59	3.61	105.9	90.9					
	Z-4		16.70	3.96	116.1	99.6					
	Z-5		19.10	4.32	126.6	106.2					
	SPEC 2		24.25	4.30	125.9	101.2					
	SPEC 3		21.40	4.34	127.0	104.6					
	SPEC 4		18.26	4.02	117.8	99.6	0	24600	6750	33°	24600
							1500	27300			
							4000	35000			
	SPEC 5		22.60	4.36	127.6	104.2					
	SPEC 8		25.15	4.13	120.8	96.4					

TABLE 5

COMPACTION METHOD	SAMPLE DESIGNATION	WORK (33750 FT-LB/FT³ UNLESS NOTED)	WATER CONTENT IN PER CENT	WEIGHT OF SOIL IN COMPACTION MOLD IN LB	WET DENSITY IN LB/FT³	DRY DENSITY IN LB/FT³	CONFINING PRESSURE LB/FT²	DEVIATOR STRESS LB/FT²	APPARENT COHESION IN LB/FT²	ANGLE OF INTERNAL FRICT. IN DEGREES	UNCONFINED COMPRESSIVE STRENGTH LB/FT²
10 LB. HAMMER; 18" STROKE; 25 BLOWS PER LAYER 3 LAYERS; 15 FT-LB PER BLOW	M-1		9.71	3.63	106.1	96.8					
	M-2		13.26	3.80	111.1	98.1	0	19720	4000	45°	19720
							1500	27400			
							4000	41400			
	M-3		16.99	4.10	119.9	102.6	0	22650	6250	31.5°	22650
							1500	26800			
							4000	32650			
	M-4		18.39	4.31	126.0	106.3	0	19950	6000	28°	19950
							1500	25000			
							4000	26600			
	M-5		21.10	4.34	127.0	104.9	0	7540	3000	22°	7540
							1500	11880			
							4000	12980			
	M-6		24.45	4.18	122.1	98.1	0	3890	1500	14°	12980
							1500	4660			
							4000	6700			
10 LB. HAMMER; 12" STROKE; 37.5 BLOWS PER LAYER; 3 LAYERS; 10 FT-LB PER BLOW	Y-3		13.82	3.82	111.8	98.3	0	21150	4600	43.5°	21150
							1500	30400			
							4000	38650			
	Y-4		15.22	3.95	115.6	100.3	0	20750	4400	41.5°	20750
							1500	27350			
							4000	36100			
	Y-5		19.00	4.32	126.3	106.1	0	12720	3250	35.5°	12720
							1500	17660			
							4000	23200			
	SPEC 1		22.2	4.31	126.0	103.1	0	6220	2000	26.5°	6220
							1500	8720			
							4000	11000			

TABLE 6

COMPACTION METHOD	SAMPLE DESIGNATION	WORK (33750 FT-LB/FT³ UNLESS NOTED)	WATER CONTENT IN PER CENT	WEIGHT OF SOIL IN COMPACTION MOLD IN LB	WET DENSITY IN LB/FT³	DRY DENSITY IN LB/FT³	CONFINING PRESSURE LB/FT²	DEVIATOR STRESS LB/FT²	APPARENT COHESION IN LB/FT²	ANGLE OF INTERNAL FRICT. IN DEGREES	UNCONFINED COMPRESSIVE STRENGTH LB/FT²
5.5 LB. HAMMER; 12" STROKE; 68.2 BLOWS PER LAYER; 3 LAYERS; 5.5 FT-LB PER BLOW	P-1		9.81	3.47	101.6	92.5					
	P-2		13.62	3.66	107.1	94.4	0	6150	1500	46°	6150
							1500	17500			
							4000	25300			
	P-3		16.89	3.90	114.2	97.8	0	15020	3750	37.5°	15020
							1500	20950			
							4000	27250			
	P-4		19.17	4.19	122.8	102.9					
	P-5		22.40	4.27	125.0	102.1					
	P-6		26.25	4.13	120.9	95.6					
	Px-1		11.27	3.48	101.9	91.6					
	Px-2		13.38	3.52	103.1	90.9	0	4870	1250	42.5°	4870
							1500	13130			
							4000	21900			
	Px-3		16.00	3.67	107.5	92.7	0	11290	2500	43°	11290
							1500	19180			
							4000	28300			
	Px-4		18.69	3.98	116.6	98.2	0	11770	3250	33°	11770
							1500	13500			
							4000	22400			
	Px-5		21.15	4.29	125.8	103.8	0	8310	2500	32°	8310
							1500	12320			
							4000	17980			
	Px-6		23.30	4.17	122.0	98.9	0	3470	1750	13.5°	3470
							1500	6400			
							4000	6390			

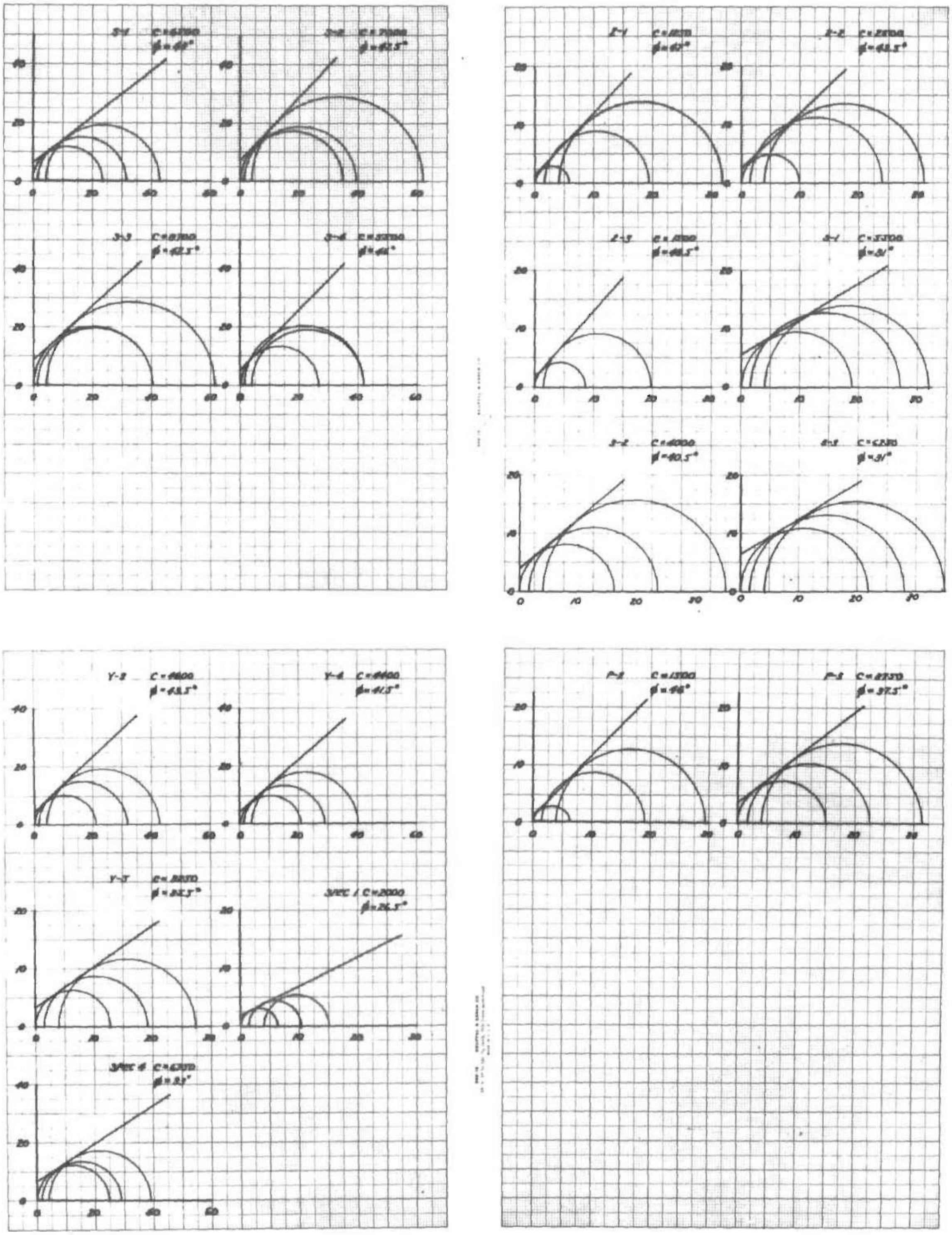


Fig. 8
MOHR'S CIRCLES

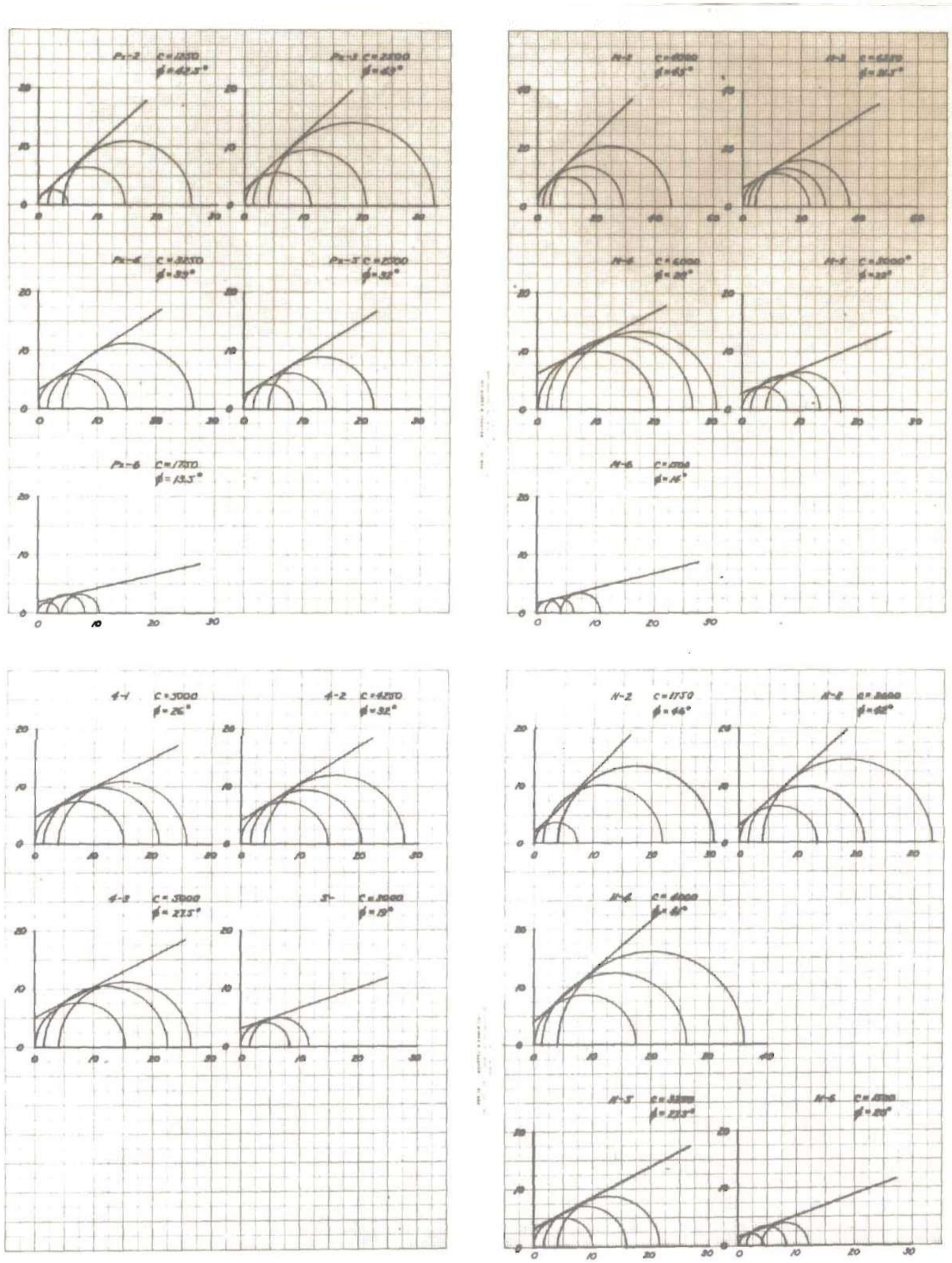
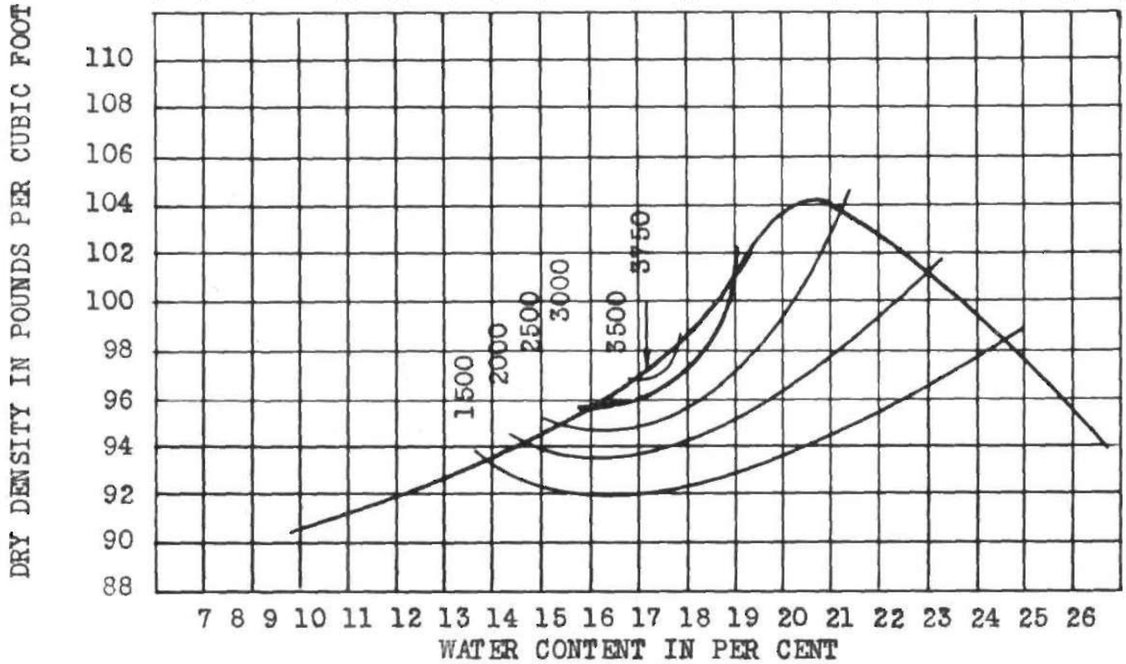
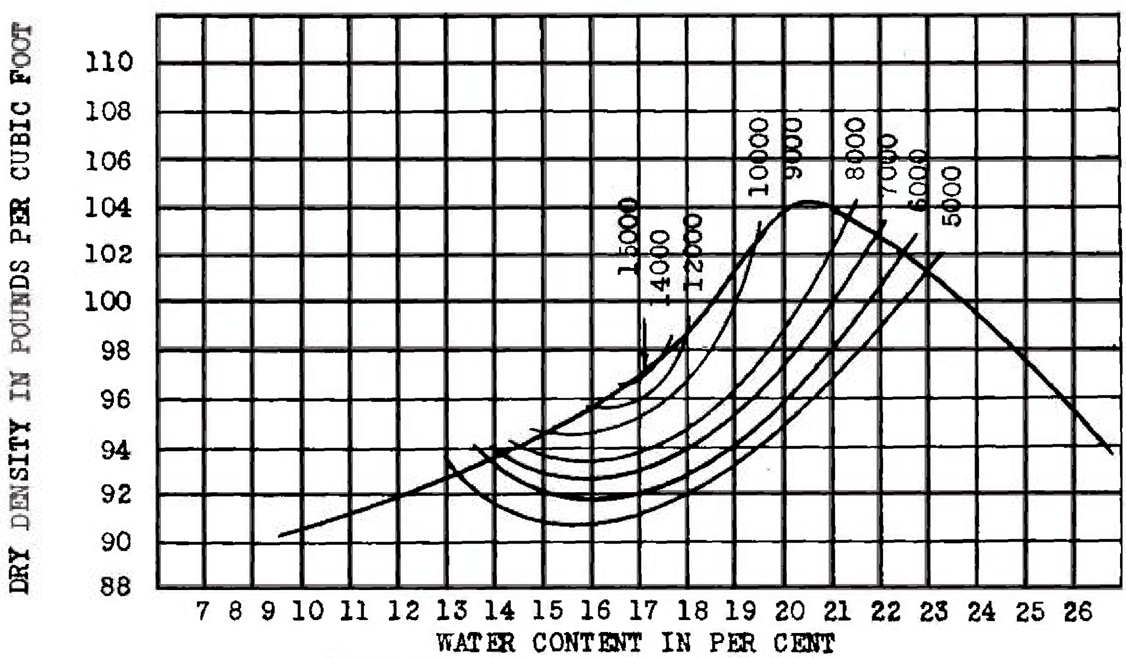


Fig. 9
MOHR'S CIRCLES



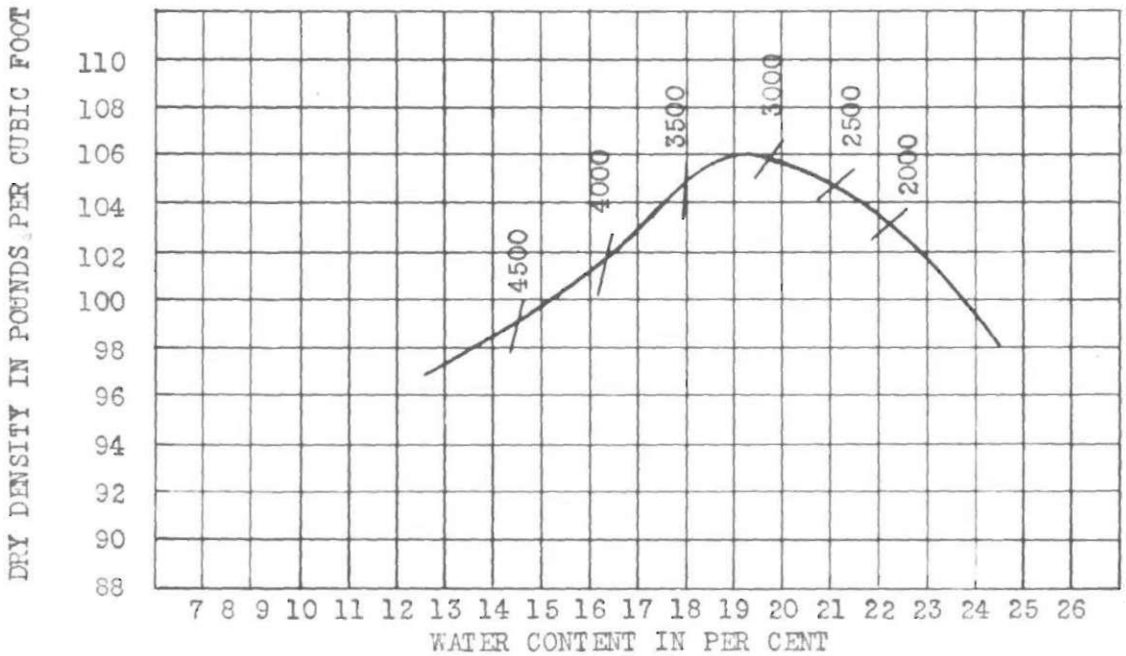
CONTOURS OF APPARENT COHESION IN POUNDS PER SQUARE FOOT



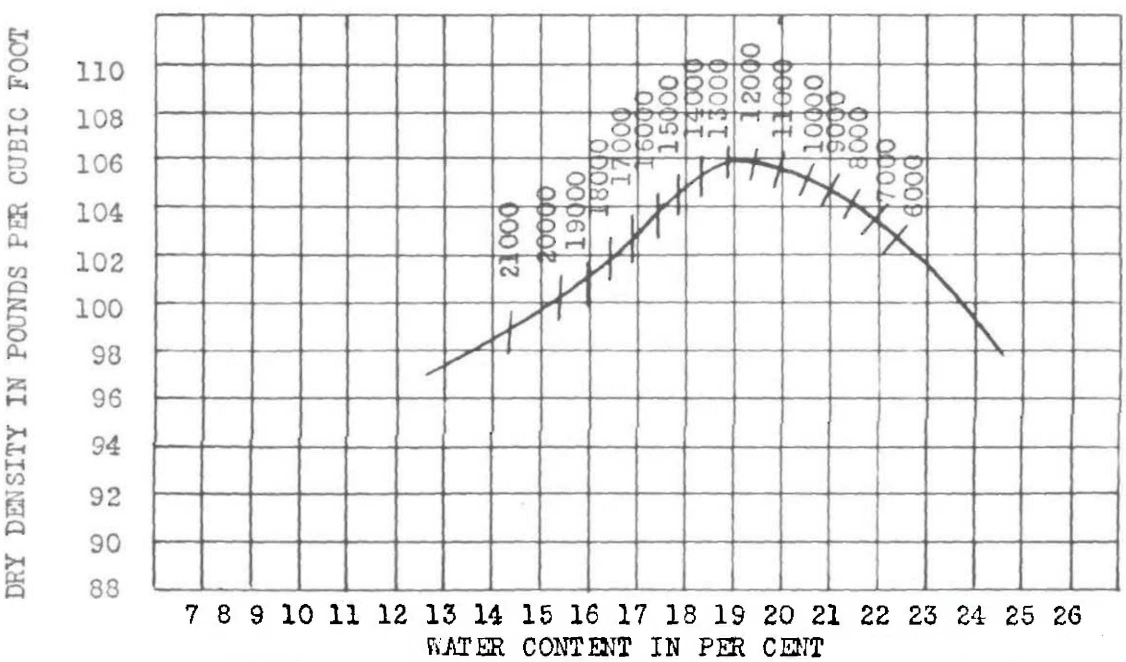
CONTOURS OF UNCONFINED COMPRESSIVE STRENGTH IN POUNDS PER SQUARE FOOT

COMPACTION (P + Px)
WORK 33750 FT-LB PER FT
55" HAMMER; 12" STROKE
68.2 BLOWS PER LAYER;
3 LAYERS

Fig. 10
CONTOURS OF APPARENT COHESION AND UNCONFINED COMPRESSIVE STRENGTH



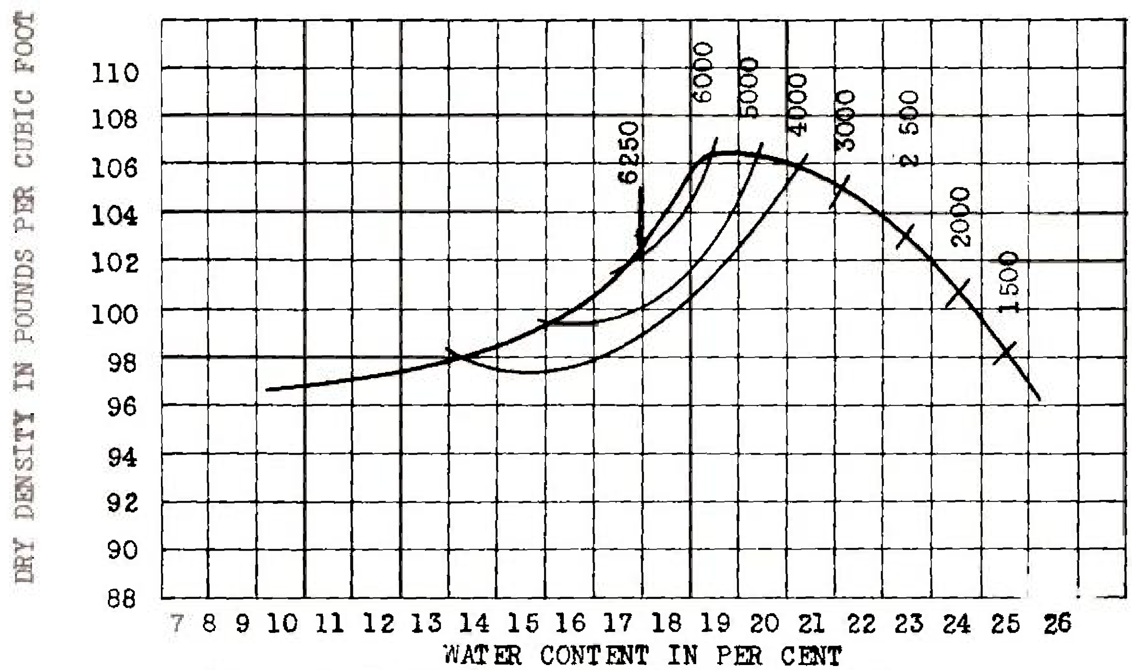
CONTOURS OF APPARENT COHESION IN POUNDS PER SQUARE FOOT



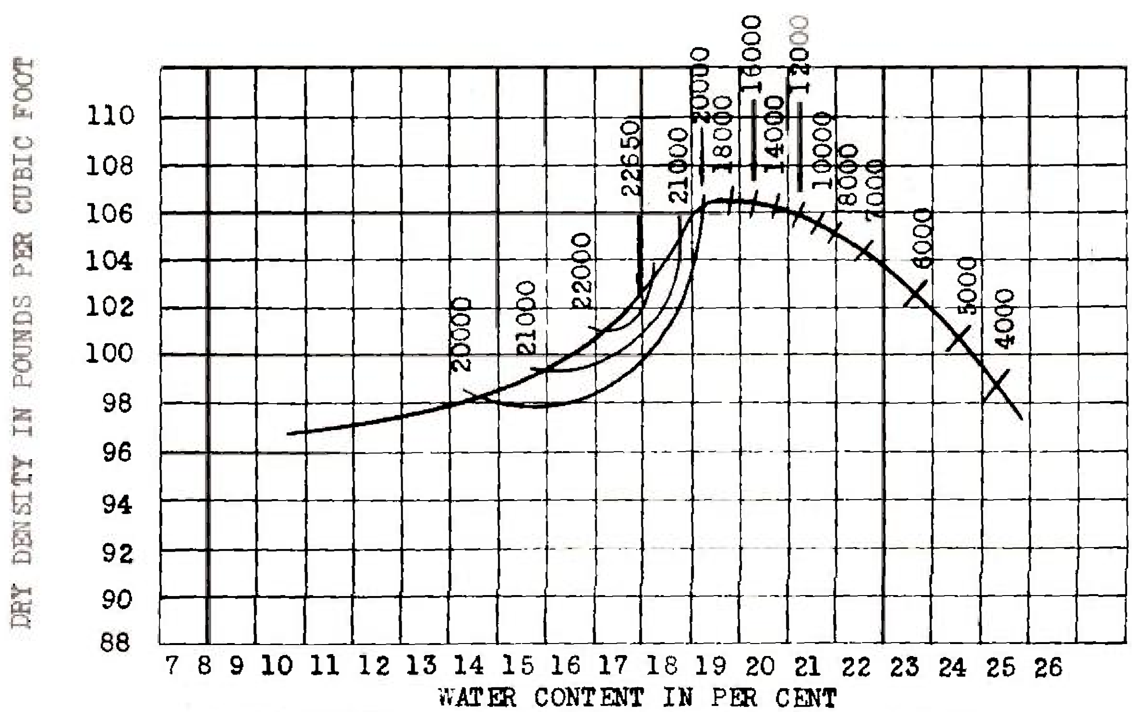
CONTOURS OF UNCONFINED COMPRESSIVE STRENGTH IN POUNDS PER SQUARE FOOT

COMPACTION (Y)
WORK 33750 FT-LB PER FT^3
10 LB HAMMER; 12" STROKE
37.5 BLOWS PER LAYER;
3 LAYERS

Fig. 11
CONTOURS OF APPARENT COHESION AND UNCONFINED COMPRESSIVE STRENGTH



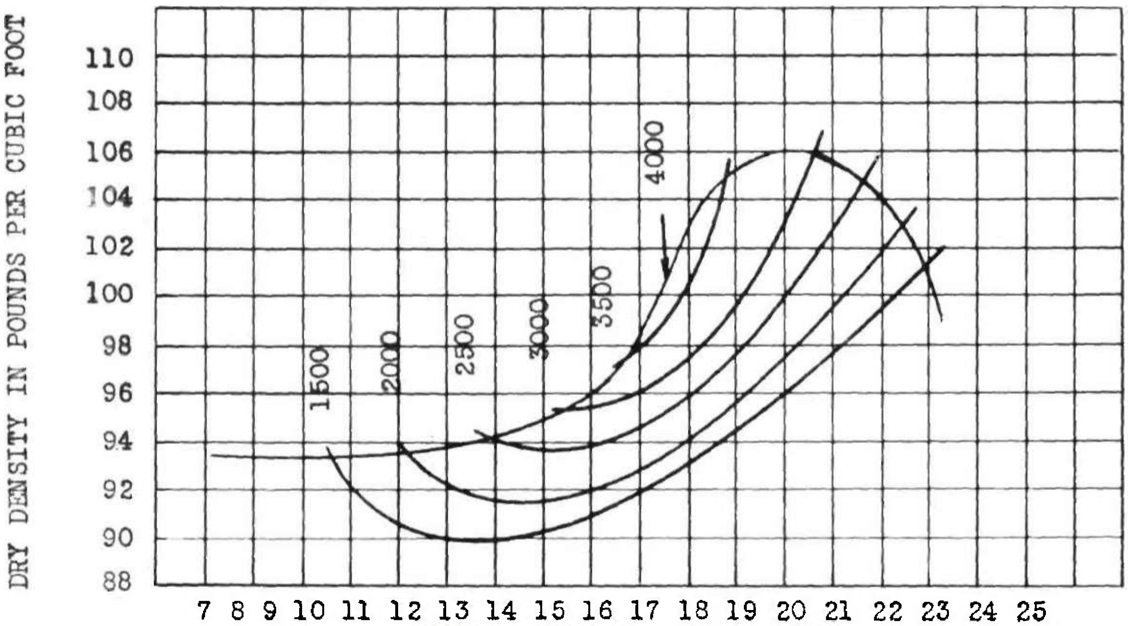
CONTOURS OF APPARENT COHESION IN POUNDS PER SQUARE FOOT



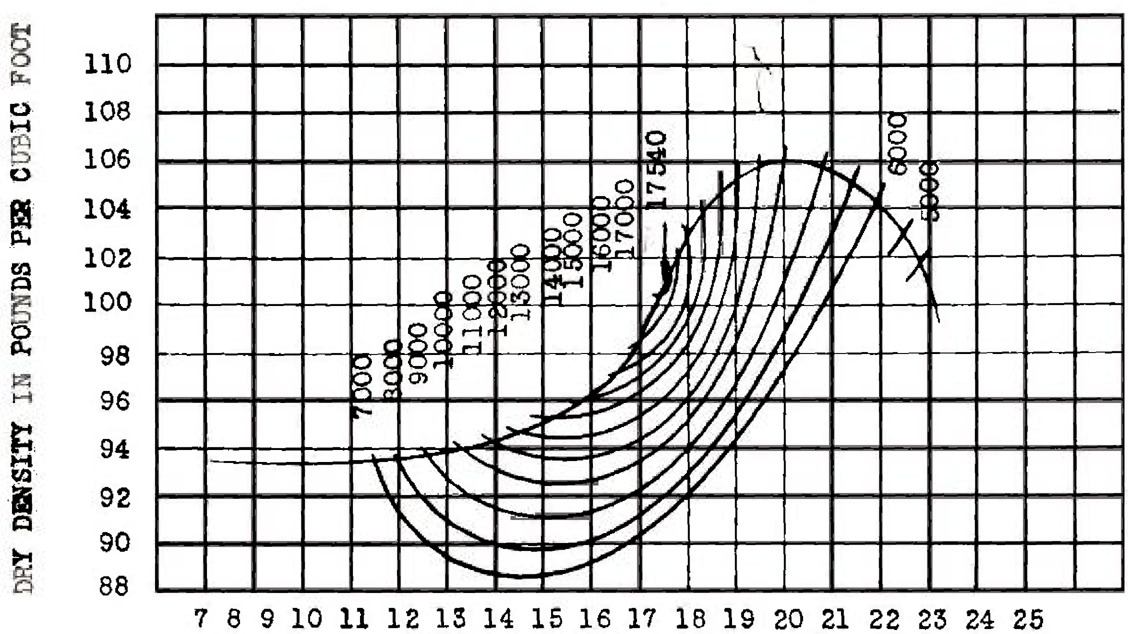
CONTOURS OF UNCONFINED COMPRESSIVE STRENGTH IN POUNDS PER SQUARE FOOT

COMPACTION (M)
WORK 33750 FT-LB PER FT^3
10 LB HAMMER; 18" STROKE
25 BLOWS PER LAYER;
3 LAYERS

Fig. 12
CONTOURS OF APPARENT COHESION AND UNCONFINED COMPRESSIVE STRENGTH



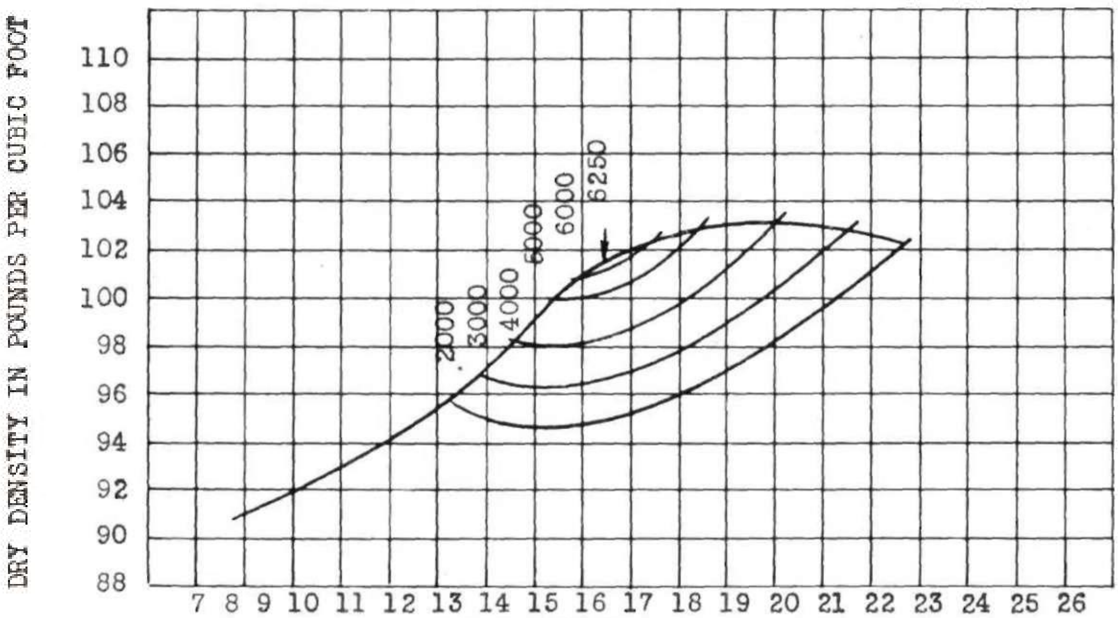
CONTOURS OF APPARENT COHESION IN POUNDS PER SQUARE FOOT



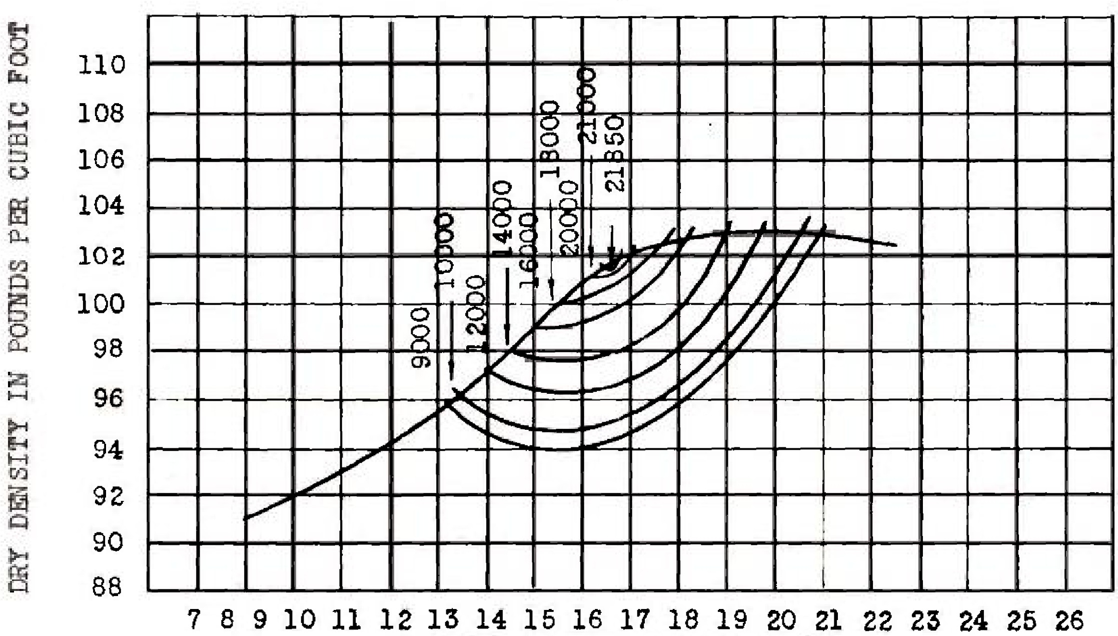
CONTOURS OF UNCONFINED COMPRESSIVE STRENGTH IN POUNDS PER SQUARE FOOT

COMPACTION (H)
WORK 33750 FT-LB PER FT^3
25 LB HAMMER; 3" STROKE
60 BLOWS PER LAYER;
3 LAYERS

Fig. 13
CONTOURS OF APPARENT COHESION AND UNCONFINED COMPRESSIVE STRENGTH



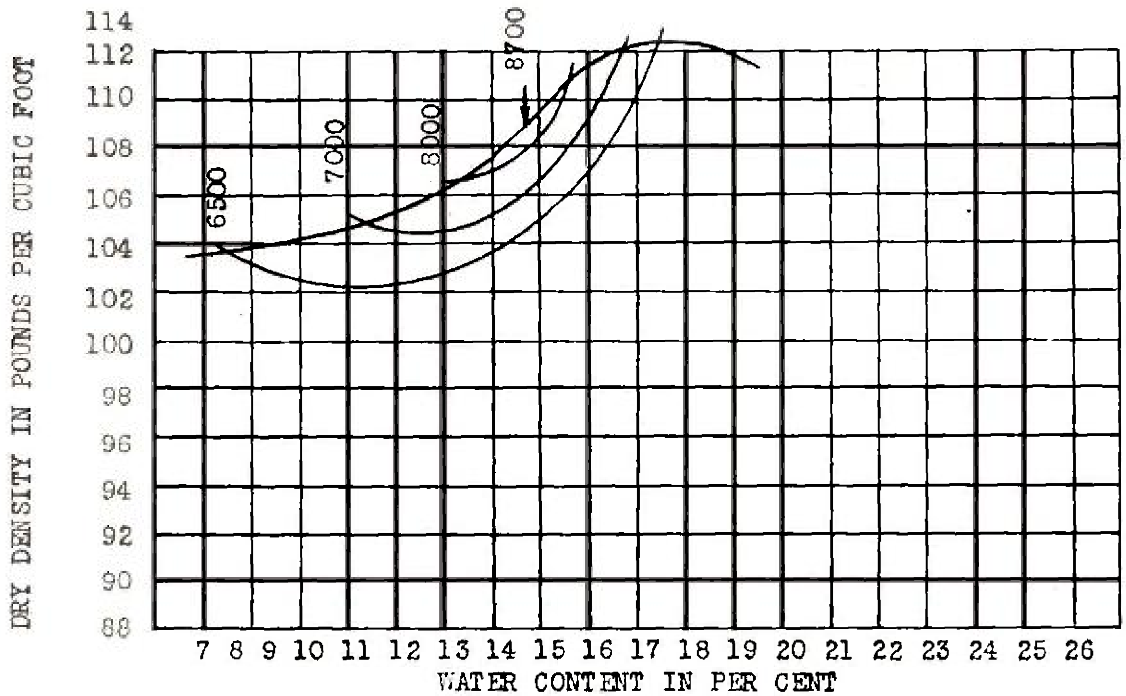
CONTOURS OF APPARENT COHESION IN POUNDS PER SQUARE FOOT



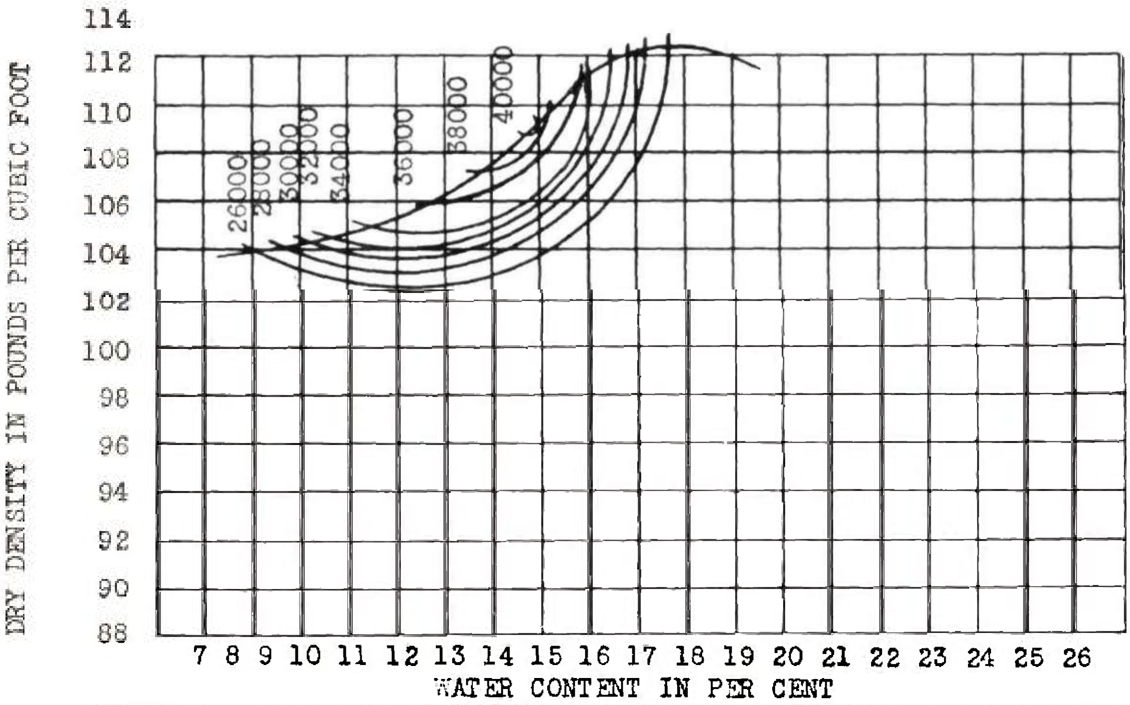
CONTOURS OF UNCONFINED COMPRESSIVE STRENGTH IN POUNDS PER SQUARE FOOT

COMPACTION
WORK 33750 FT-LB PER FT^3
STATIC PUNCHING
3 LAYERS

Fig. 10
CONTOURS OF APPARENT COHESION AND UNCONFINED COMPRESSIVE STRENGTH



CONTOURS OF APPARENT COHESION IN POUNDS PER SQUARE FOOT

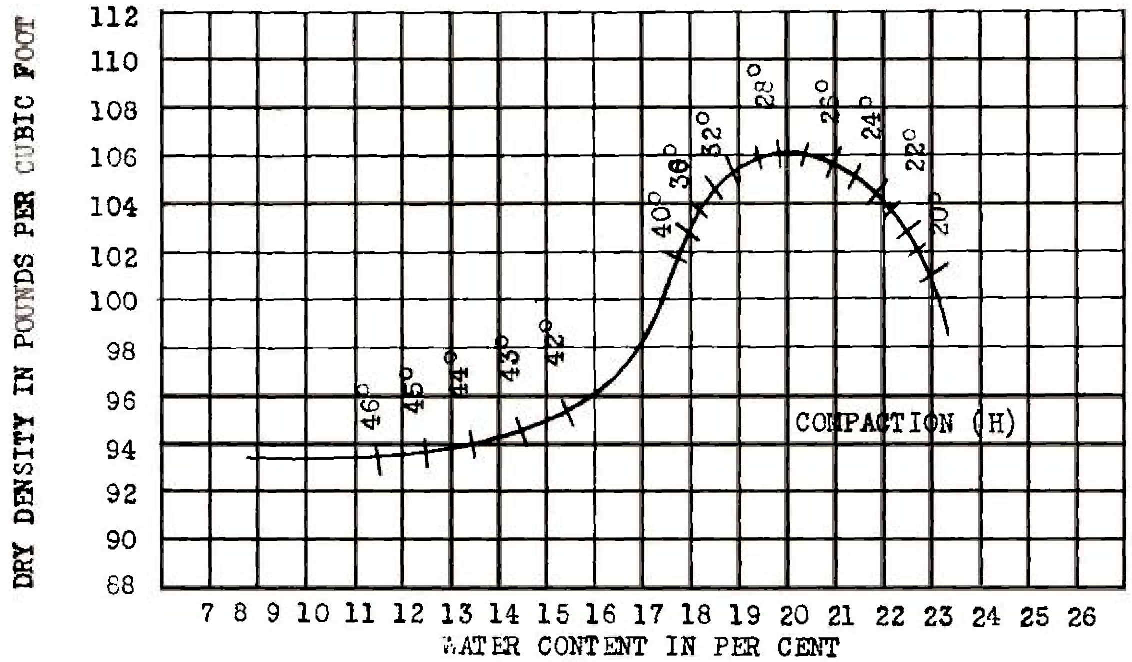


CONTOURS OF UNCONFINED COMPRESSIVE STRENGTH IN POUNDS PER SQUARE FOOT

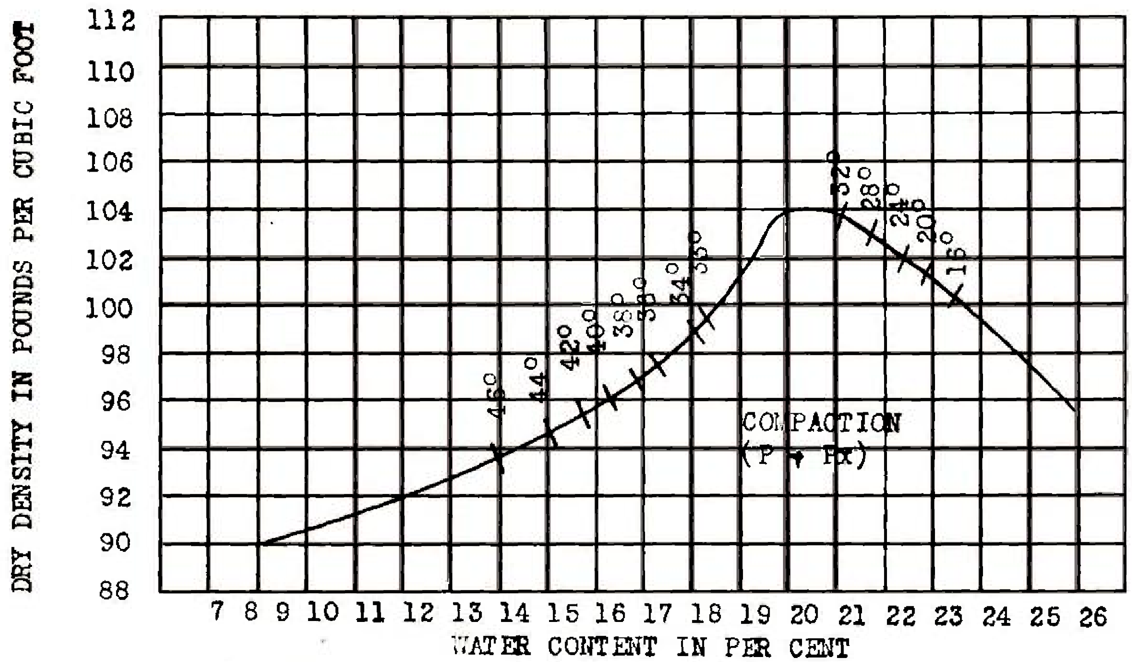
COMPACTION (S)
WORK 33750 FT-LB PER FT^3
STATIC COMPACTION
3 LAYERS

Fig. 15

CONTOURS OF APPARENT COHESION AND UNCONFINED COMPRESSIVE STRENGTH

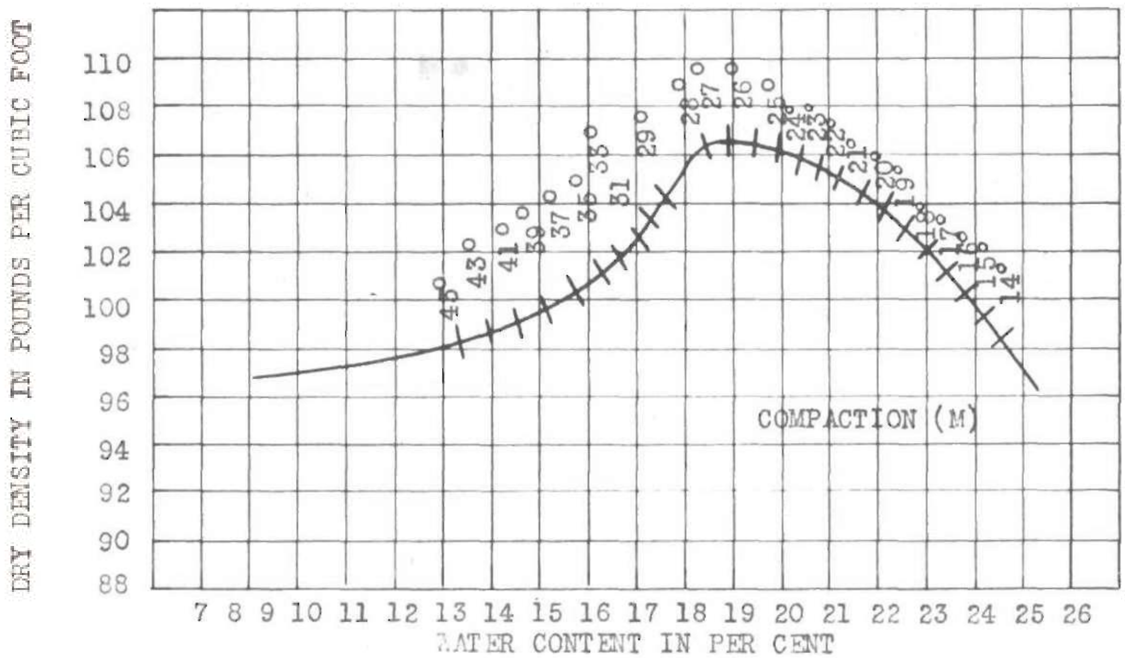


CONTOURS OF ANGLE OF INTERNAL FRICTION IN DEGREES

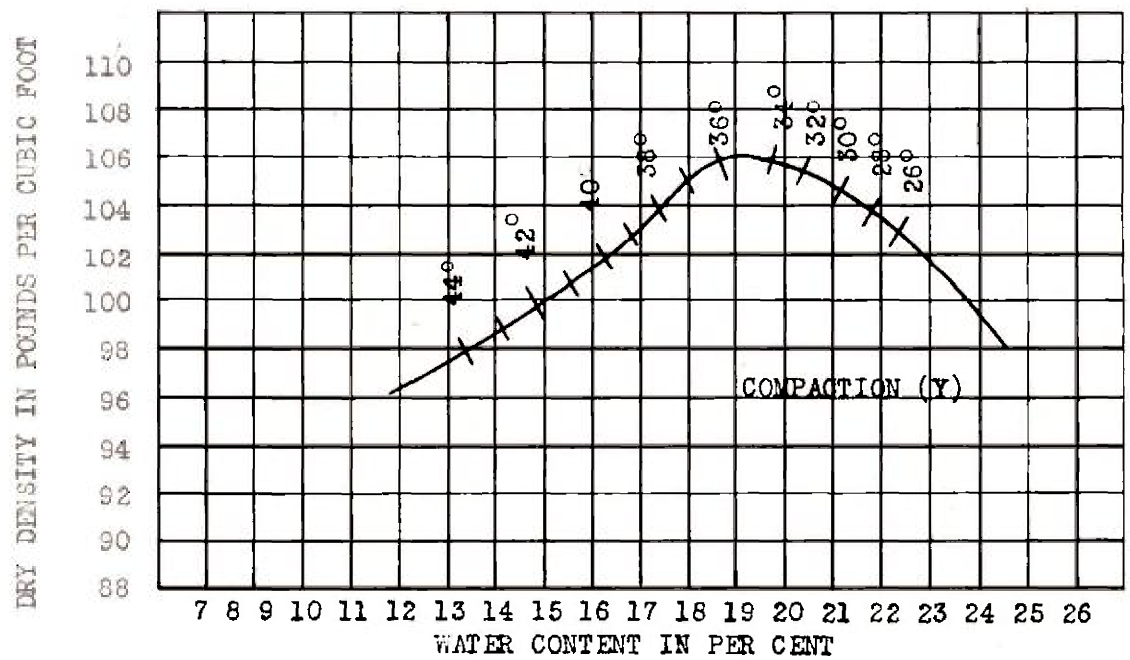


CONTOURS OF ANGLE OF INTERNAL FRICTION IN DEGREES

Fig. 16
CONTOURS OF ANGLE OF INTERNAL FRICTION FOR COMPACTIONS
P, Px, AND H



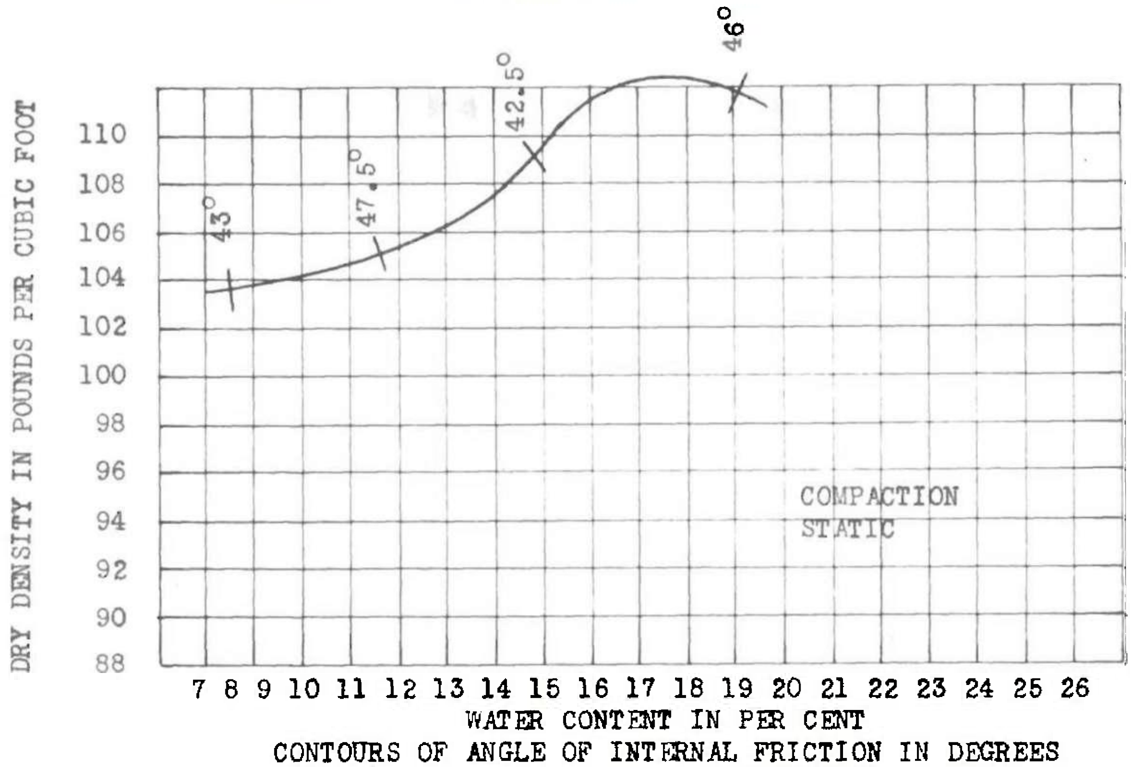
CONTOURS OF ANGLE OF INTERNAL FRICTION IN DEGREES



CONTOURS OF ANGLE OF INTERNAL FRICTION IN DEGREES

Fig. 17

CONTOURS OF ANGLE OF INTERNAL FRICTION FOR COMPACTIONS M AND Y



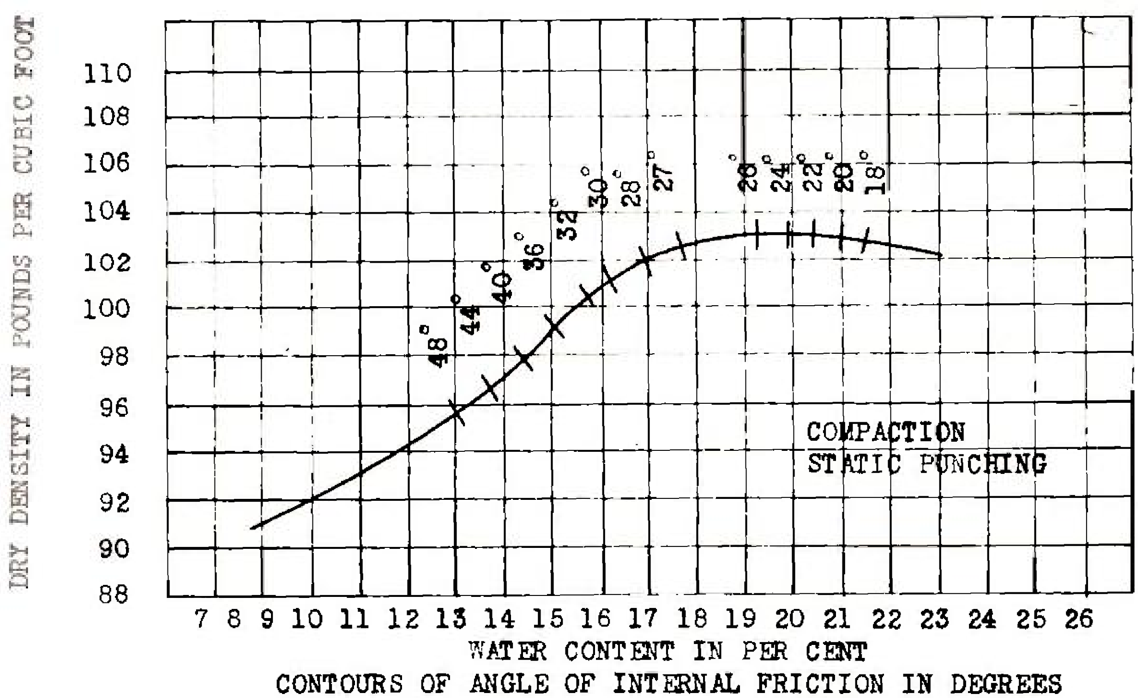
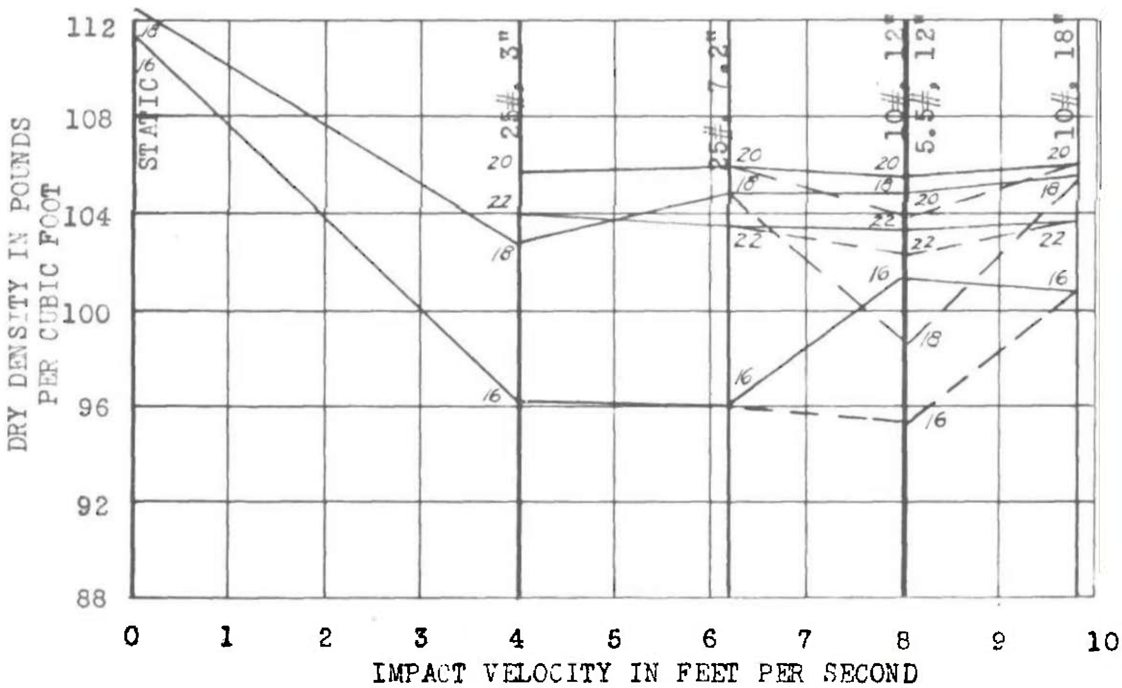


Fig. 18
CONTOURS OF ANGLE OF INTERNAL FRICTION



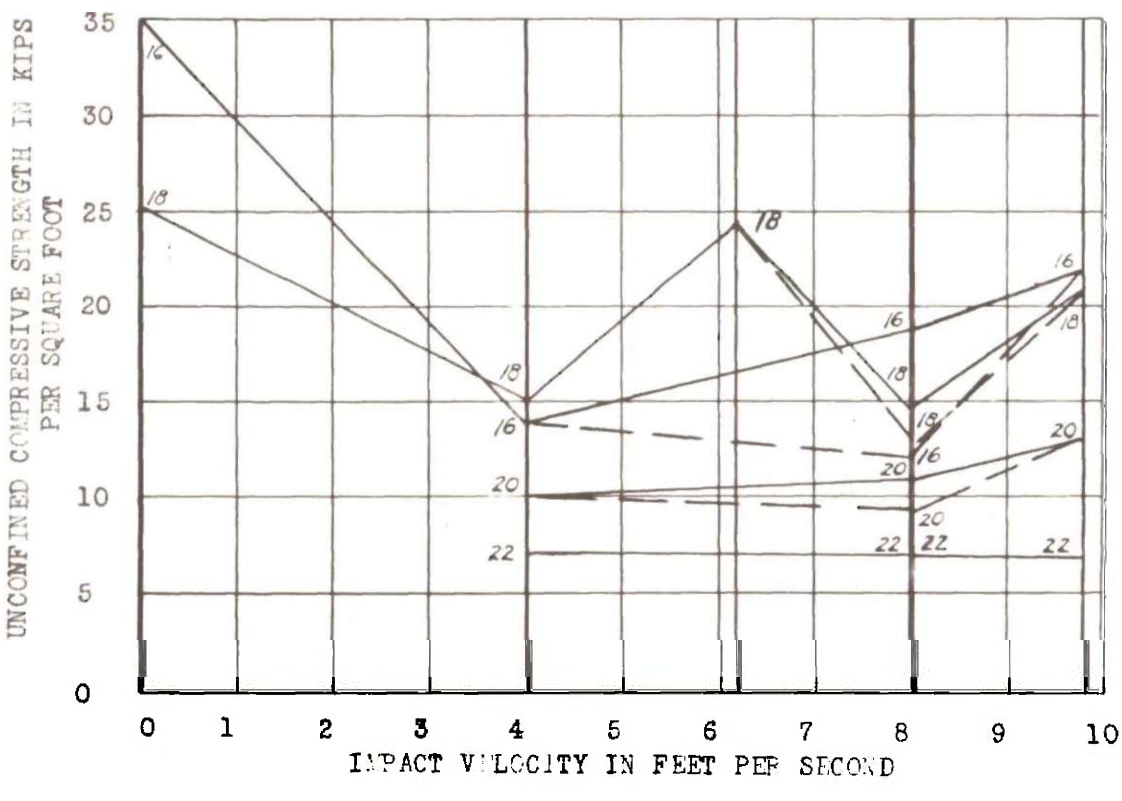


Fig. 19
VELOCITY OF IMPACT RELATIONSHIPS AT VARIOUS WATER CONTENTS

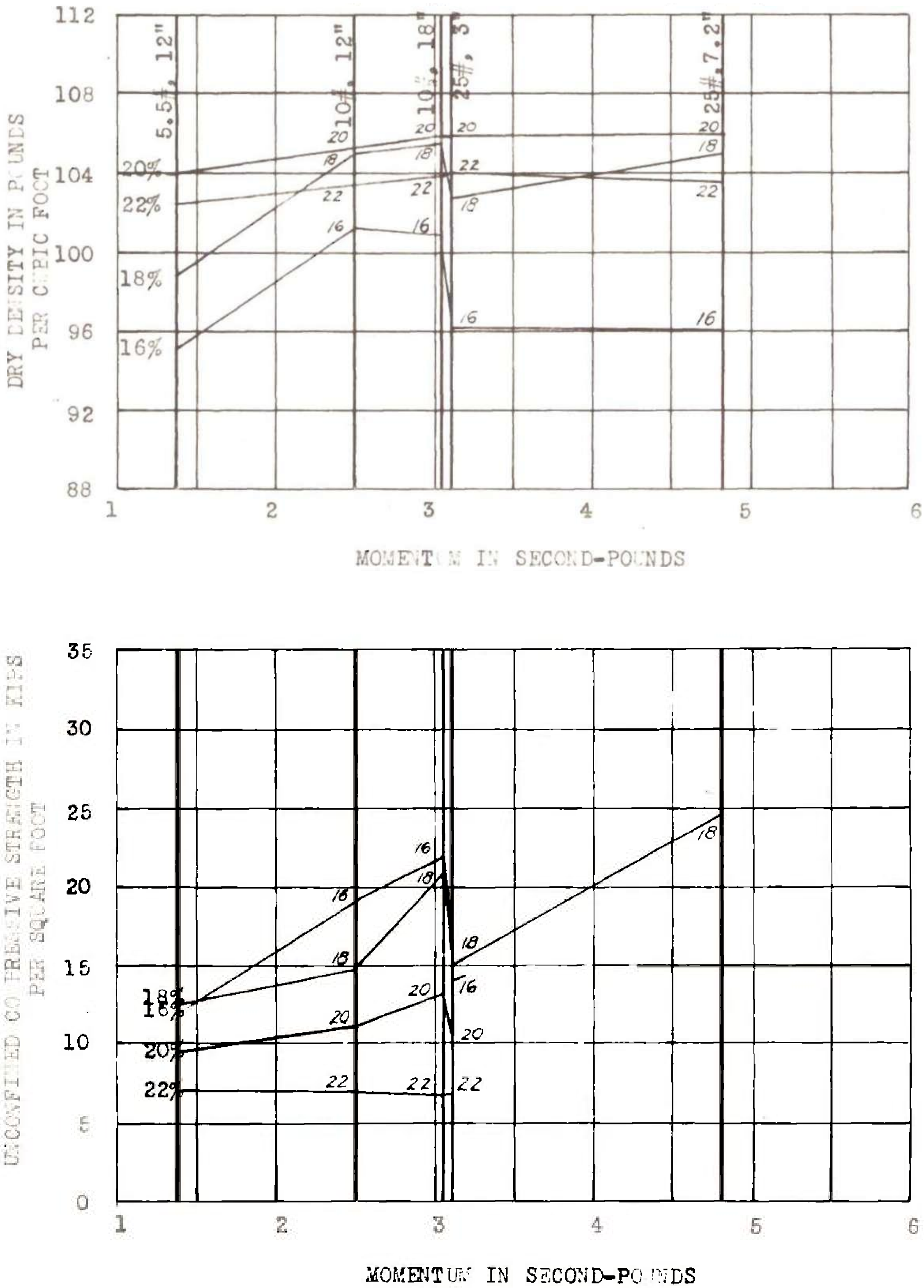


Fig. 20

MOMENTUM RELATIONSHIPS AT VARIOUS WATER CONTENTS

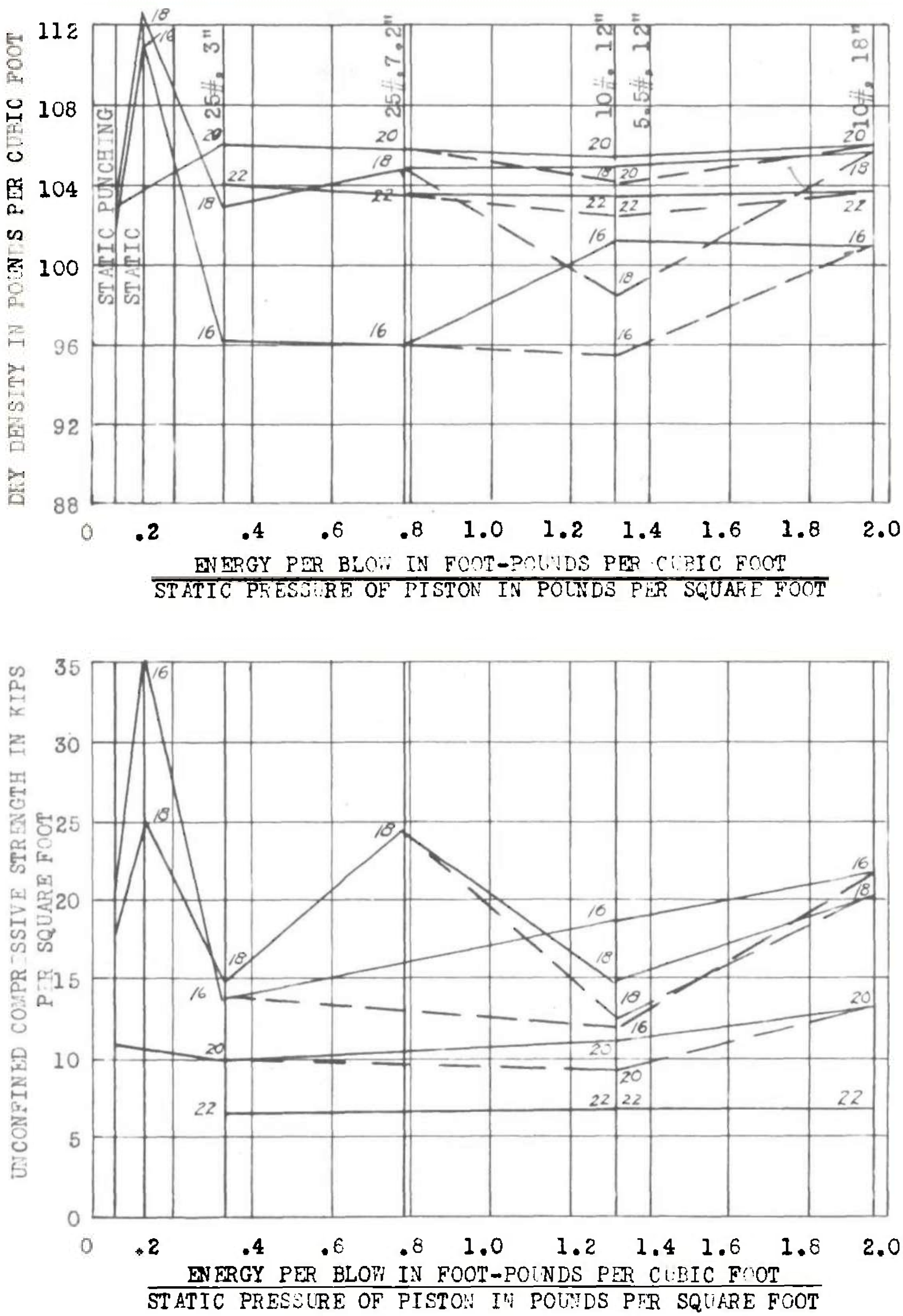


Fig. 21
DYNAMIC-STATIC PRESSURE RELATIONSHIPS
AT VARIOUS WATER CONTENTS

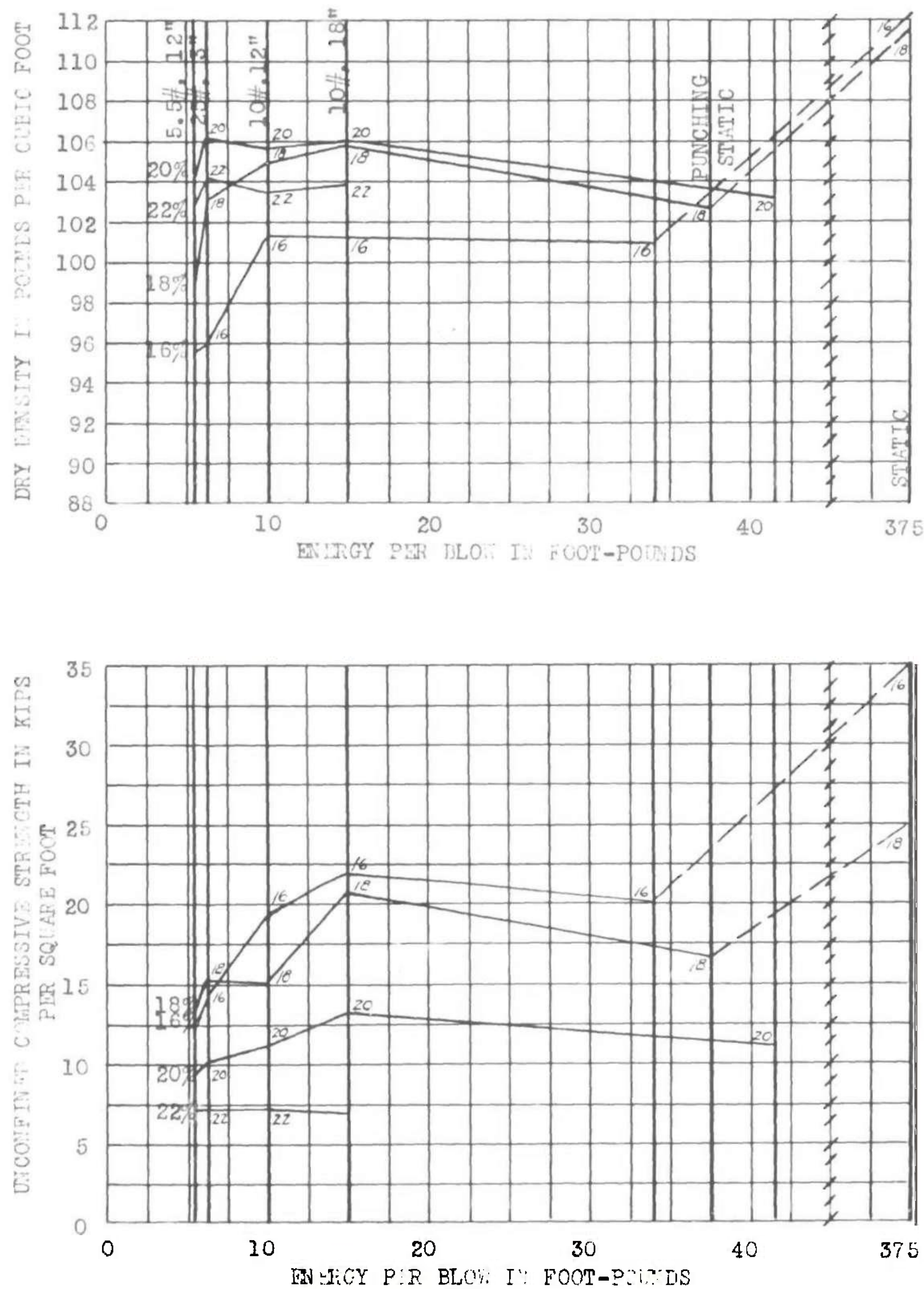
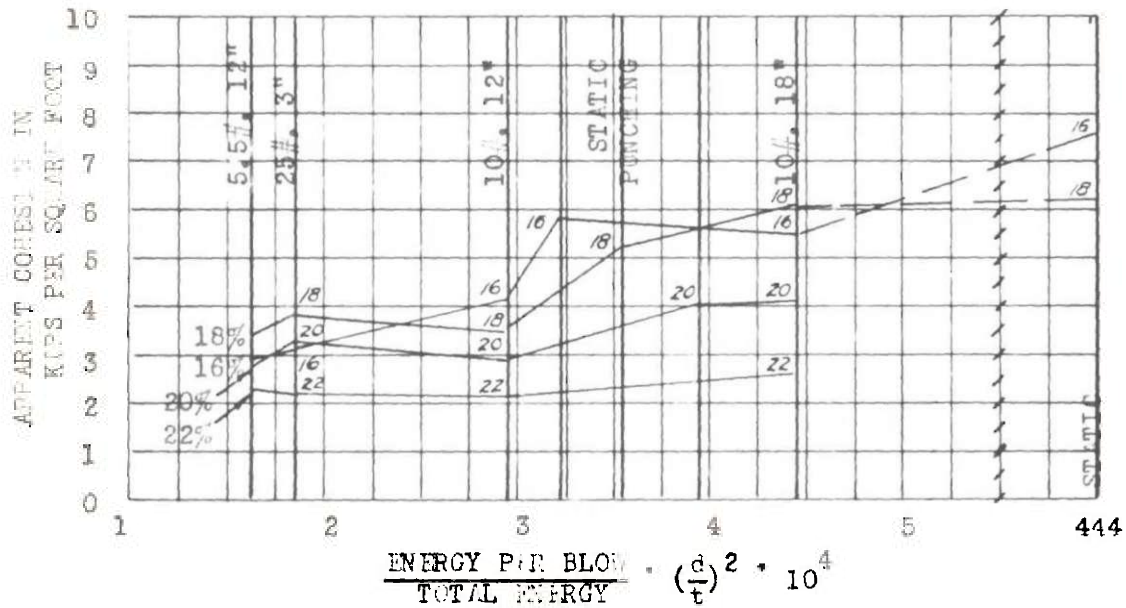


Fig. 22

ENERGY PER BLOW RELATIONSHIPS AT VARIOUS WATER CONTENTS



NOTE: d = DIAMETER OF PISTON OR HAMMER
t = THICKNESS OF LAYER COMPACTED

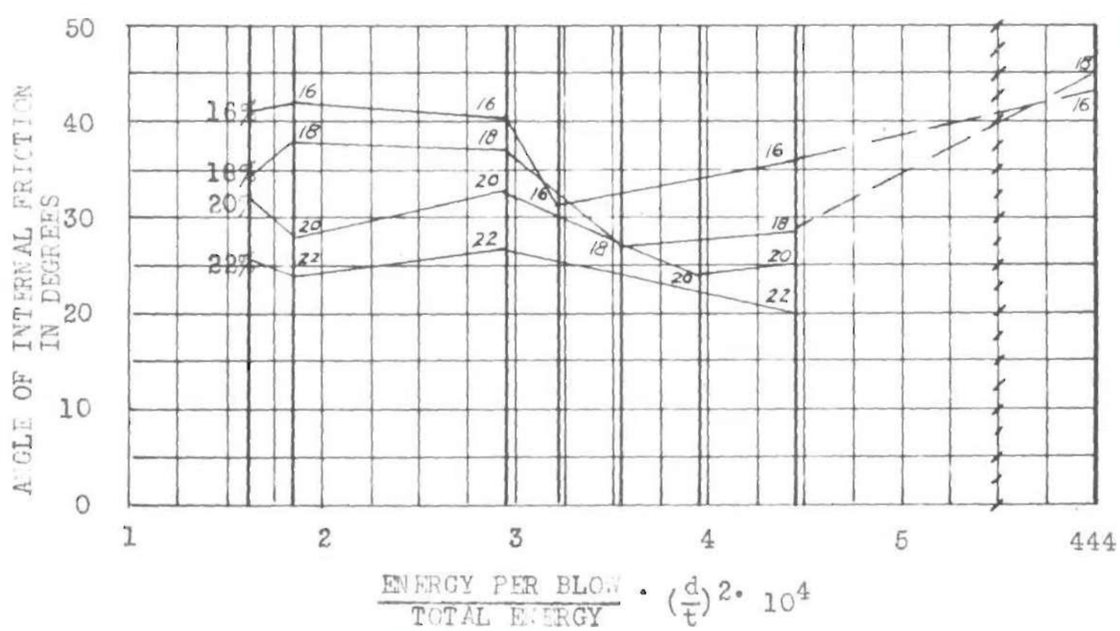
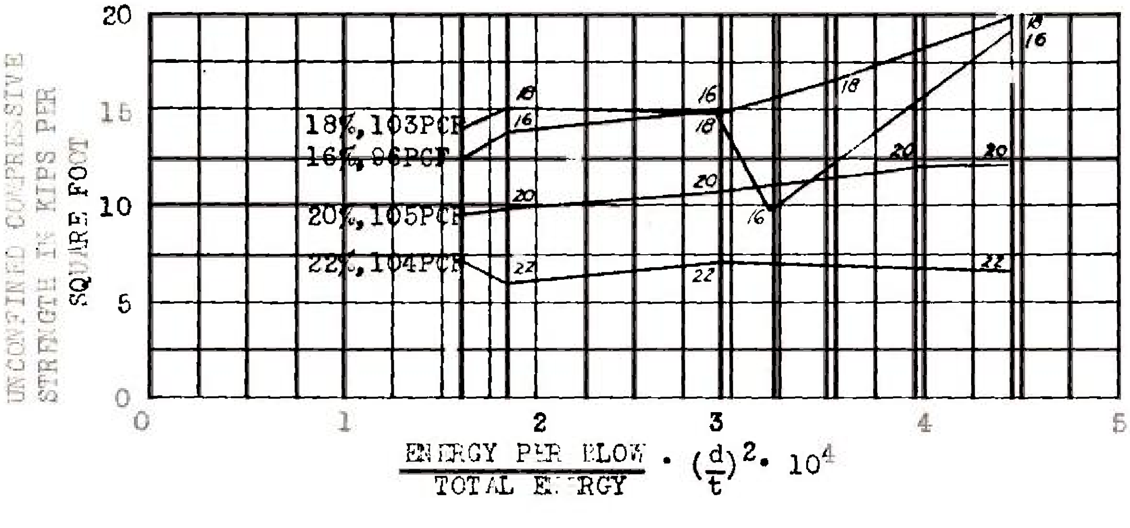


Fig. 23
MODIFIED ENERGY PER BLOW VERSUS APPARENT COHESION
AND ANGLE OF INTERNAL FRICTION



NOTE: d = DIAMETER OF PISTON OF HAMMER
t = THICKNESS OF LAYER COMPACTED

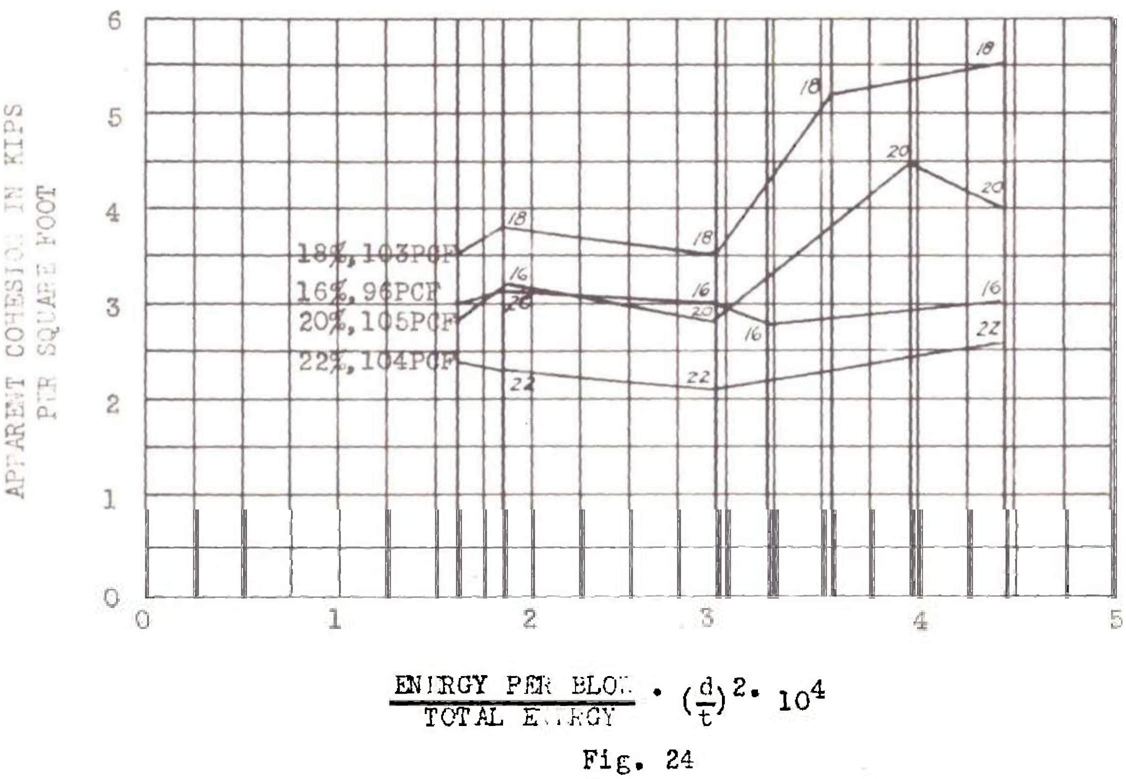
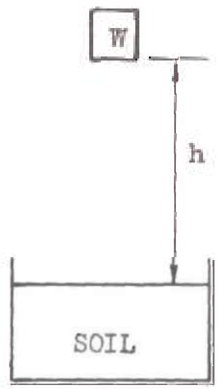
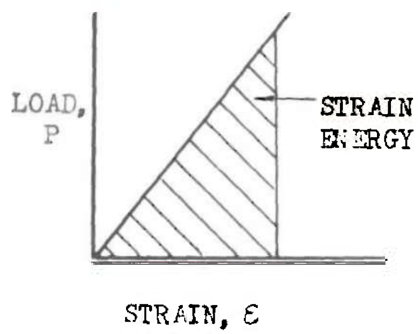


Fig. 24

MODIFIED ENERGY PER BLOW RELATIONSHIPS AT SEVERAL ARBITRARY POINTS

AN ENERGY PER BLOW - DYNAMIC PRESSURE RELATIONSHIP





Compaction is being performed by the weight W. Assuming that the total work produced by the falling weight W is transferred into strain energy, one finds that

$$W(h + e) = \frac{Pe}{2}$$

where
- W = falling weight in pounds
- P = equivalent static load in pounds
- e = deformation in inches
- A = area of face of weight striking the soil
- E = modulus of elasticity of the soil
- t = thickness of layer being compacted

$$E = \frac{Pt}{AE} \text{ or } P = \frac{EAe}{t}$$

Therefore $W(h+e) = \frac{EAe}{t} \cdot \frac{e}{2} = \frac{EAe^2}{2t}$

$$e = \frac{EAe^2}{2tW} - h$$

Let e_s = static elongation produced by W

$$e_s = \frac{Wt}{AE}$$

Therefore $e = \frac{EAe^2t}{2tEAe_s} - h = \frac{e^2}{2e_s} - h$

For a falling weight $h = \frac{v^2}{2g}$

Therefore, substituting $\frac{v^2}{2g}$ for h in the above and solving the quadratic for e, one obtains

$$e = \frac{2e_s g + \sqrt{4e_s^2 g^2 - 4e_s v^2 g}}{2g}$$

or
$$e = e_s + \sqrt{e_s^2 + \frac{e_s v^2}{g}}$$

If $h \gg e_s$, then $e_s \ll \frac{e_s v^2}{g}$ and e_s can be neglected.

Let S = stress in the soil

$$S = \frac{Ee}{t} = \frac{E}{t}\sqrt{\frac{e_s v^2}{g}}$$

or
$$S^2 = \frac{E^2}{t^2} \cdot \frac{e_s v^2}{g}$$

but
$$e_s = \frac{Wt}{AE}$$

Therefore
$$S = \sqrt{\left(\frac{2E}{At}\right)\left(\frac{Wv^2}{2g}\right)}$$

or
$$S = \sqrt{\frac{2 \cdot E \cdot (\text{Energy Input})}{\text{Volume}}}$$

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